Towards New Source of Matter-Antimatter Asymmetry

— Experimental Techniques and Future Prospects for EDM Searches at the LHC

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CONTENT

1

Why MEDM?

EDM and MDM of fundamental particles

In a quantum system, for spin ½ particles:

Electric dipole moment (**EDM**)

$$\boldsymbol{\delta} = \frac{1}{2} d \mu_B \mathbf{P}$$

Magnetic dipole moment (**MDM**)

$$\boldsymbol{\mu} = \frac{1}{2} g \mu_B \mathbf{P}$$

Spin polarization vector:

$$\mathbf{P} = \mathrm{Tr}[\rho \boldsymbol{\sigma}] = \frac{2}{\hbar} < \hat{\boldsymbol{S}} >$$

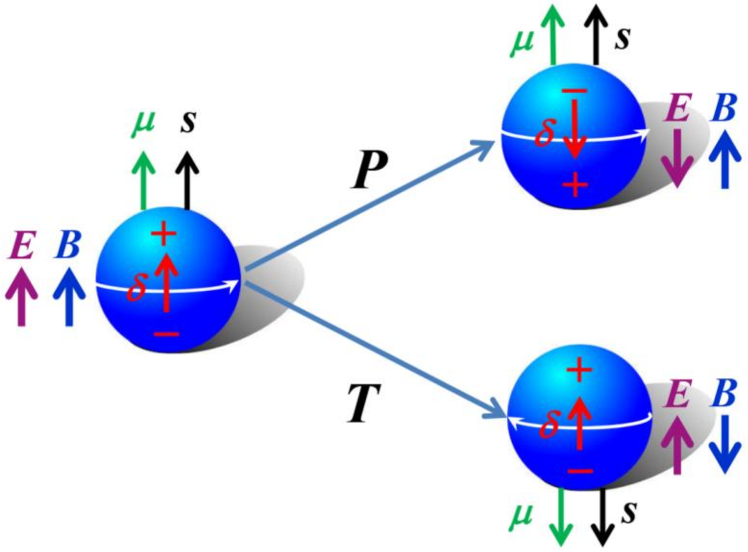
Magneton: μ_B

Gyro-electric(magnetic) factor: $d(g)$

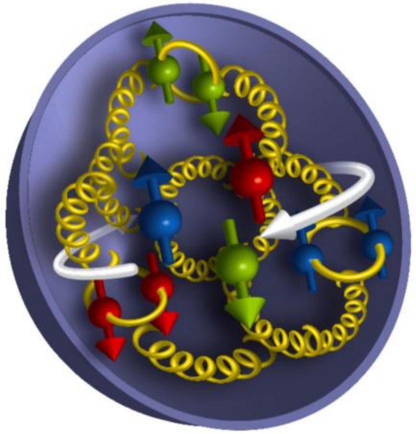
$$\mathcal{H} = -\boldsymbol{\mu} \cdot B - \boldsymbol{\delta} \cdot \boldsymbol{E}$$

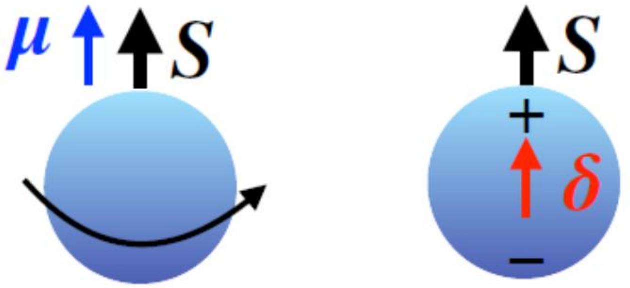
$$\mathcal{H} \xrightarrow{\mathrm{P,T}} \mathcal{H} = -\boldsymbol{\mu} \cdot B + \boldsymbol{\delta} \cdot \boldsymbol{E}$$

Non-zero EDM is a signal of P/T, and CP violation



Dipole moments are sensitive to **baryon substructure**. Arise from electric charge and current distributions inside baryons





New physics with EDM

- Big matter and anti-matter asymmetry founded in the universe.

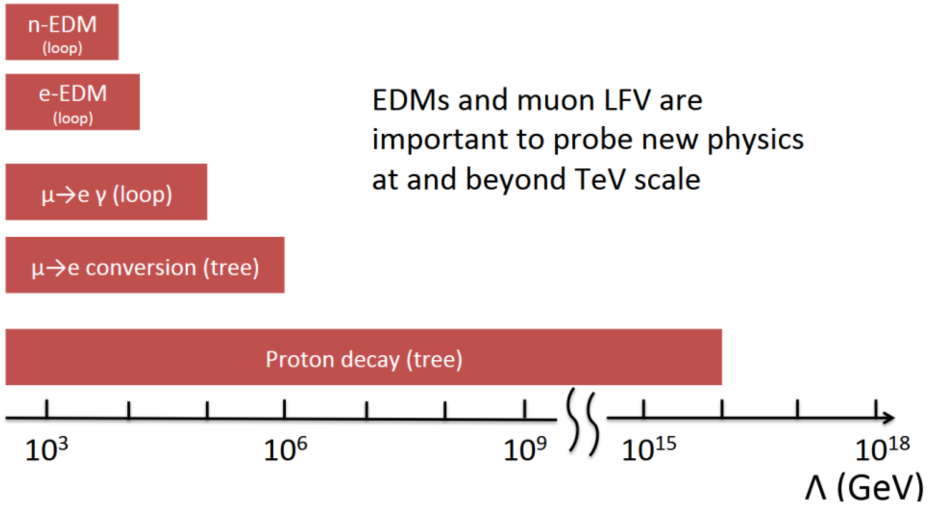
$$(n_B - n_{\bar{B}})/n_\gamma|_{CMB} = (6.08 \pm 0.09) \times 10^{-10}$$

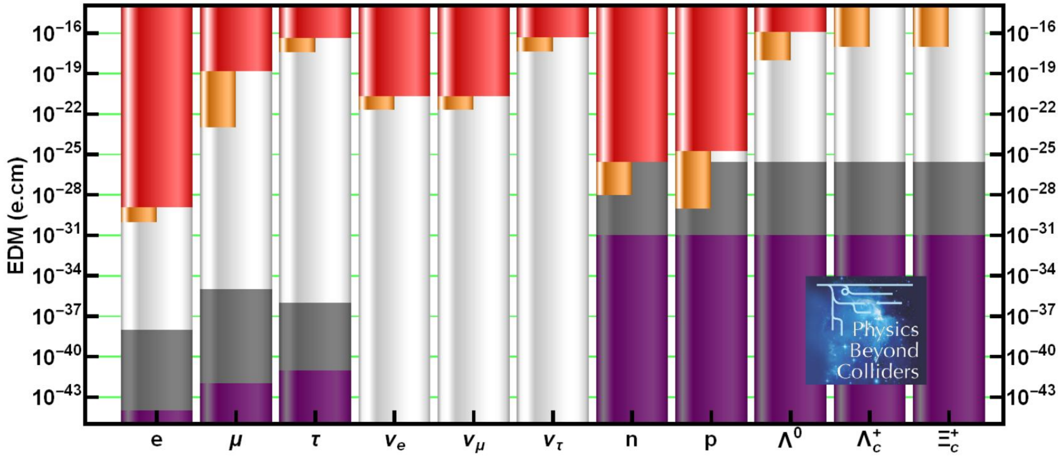
- CP violation has been founded at K, B, D meson system, but not enough to explain matter dominant universe. New CP violation sources beyond SM are needed to explain predominance of matter over antimatter.

SM prediction: $\hat{d}_{CP} = \frac{d_{CP}}{D^{12}} \sim 10^{-18} \ll 10^{-10}$

- EDM is one of the few low energy measurements sensitive to fundamental particle physics at a scale of few TeV and above.

$$d_e \sim e\frac{m_e}{M^2} = 10^{-23} e\ \mathrm{cm}\left(\frac{1\ \mathrm{TeV}}{M}\right)^2$$





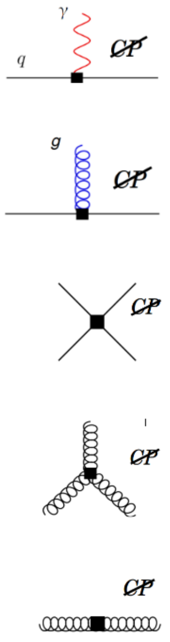
J. Phys. G: Nucl. Part. Phys. 47 (2020) 010501

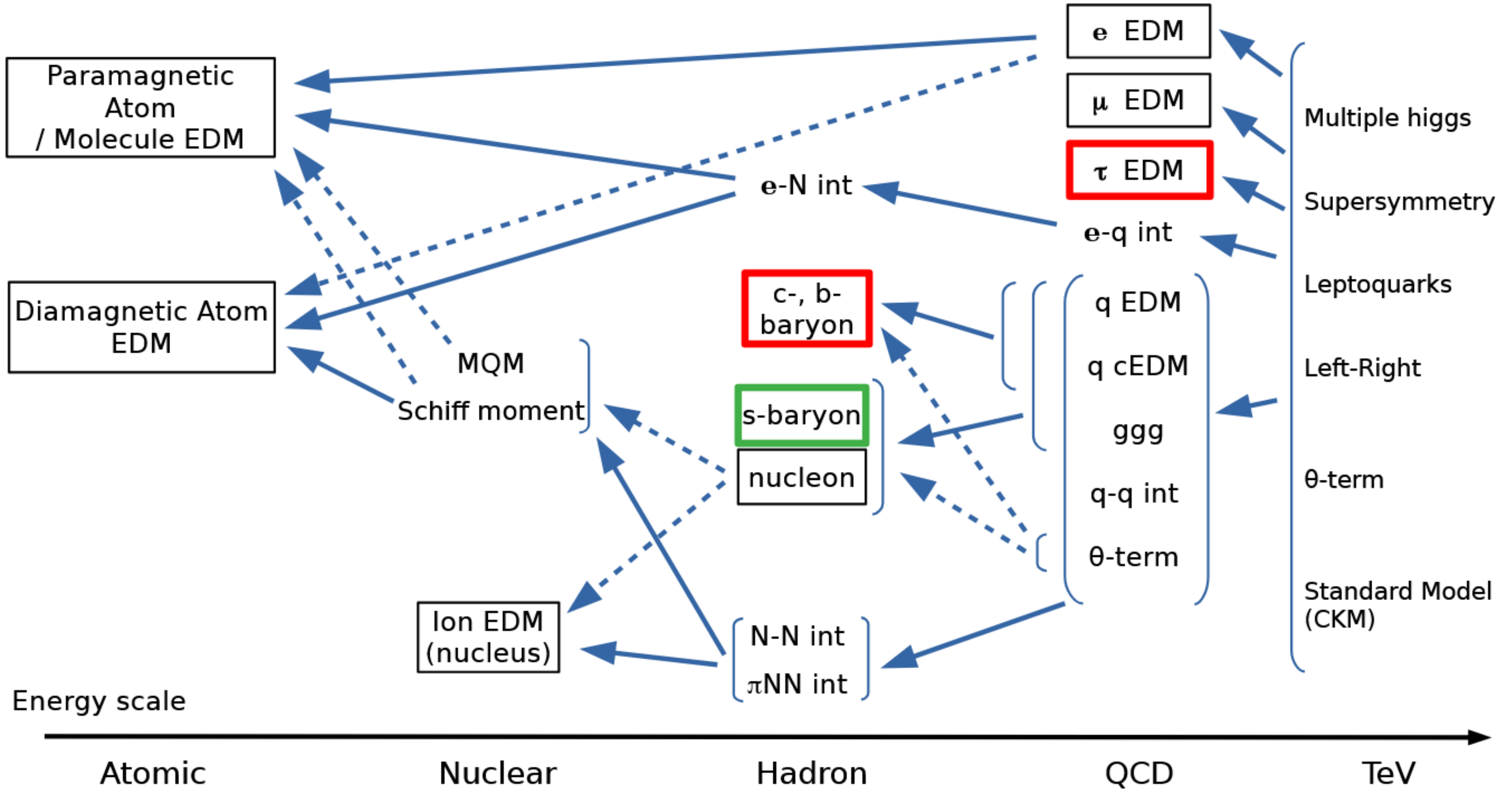
Why search for EDM in different system?

- The search in **different systems** (leptons, nucleons, atoms, molecules) **are complementary** and needed to **discriminate between EDM sources**.
- Important: different BSM models a different EFT operators

Doctor thesis of Joan Ruiz-Vidal: arXiv:2407.19247

$$\mathcal{L}_{\rm eff}^{\not{P}\not{T}} = -\frac{i}{2}\sum_{q=u,d,s,c,b} d_q\, \bar{q}\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu} - \frac{i}{2}\sum_{q=u,d,s,c,b} \tilde{d}_q\, \bar{q}\sigma^{\mu\nu}\gamma_5 T_a q\, G^a_{\mu\nu} + \sum_{i,j,k,l=u,d,s,c,b} C_{ijkl}\, \bar{q}_i\Gamma q_j\, \bar{q}_k\Gamma' q_l + \frac{w}{6} f_{abc}\varepsilon^{\mu\nu\alpha\beta}G^a_{\alpha\beta}G^b_{\mu\rho}G^{c\,\rho}_{\nu} - \bar{\theta}\frac{g^2}{64\pi^2}\epsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta}$$





Hyperon EDM: theoretical aspect

Depends on inner structure, could be estimated using QCD models and LQCD

i.e. chiral perturbative QCD assuming from strong CP ($10^{-16}\, e\, \bar{\theta}$ cm)

F-K Guo et al, JHEP 12(2012) 097

$$d_n = -2.9 \pm 0.4 \pm 0.8,$$

$$d_p = 1.1 \pm 0.5 \pm 1.0$$

$$d_\Lambda = -2.5 \pm 0.2 \pm 0.4, \quad d_{\Sigma^+} = -0.7 \pm 0.5 \pm 1.0,$$

$$d_{\Sigma^0} = 0.7 \pm 0.2 \pm 0.4, \quad d_{\Sigma^-} = 2.2 \pm 0.5 \pm 0.2$$

$$d_{\Xi^0} = -3.4 \pm 0.4 \pm 0.8, \quad d_{\Xi^-} = 0.6 \pm 0.5 \pm 0.2.$$

LQCD, only neutron?

Charmed baryon EDM: theoretical aspect

TABLE IV. Contributions to the EDMs of the antitriplet baryons for $\Lambda = 1$ TeV. The results are given in $10^{-19}\ e$ cm and $10^{-20}\ e$ cm for the qEDM and qCEDM operators, respectively, and $10^{-21}\ e$ cm for the 4q and 4qLR operators.

Contribution	Λ_c^+	Ξ_c^0	Ξ_c^+
qEDM	-0.14 ± 1.79	-0.14 ± 1.79	-0.14 ± 1.79
qCEDM	-0.10 ± 3.10	$+0.12 \pm 2.7$	-0.10 ± 3.10
4q	$+0.17 \pm 5.3$	$+0.17 \pm 4.4$	$+0.13 \pm 3.9$
4qLR	$+0.12 \pm 2.6$	-0.15 ± 2.5	-0.11 ± 2.4

Phys. Rev. D 108, no.7, 075023 (2023)

- Neutron EDM provides a **strict limit** on the contribution from light quarks → Assume the EDM of charmed baryons comes only from charm quark
- At $O(10^{-19})e$ cm

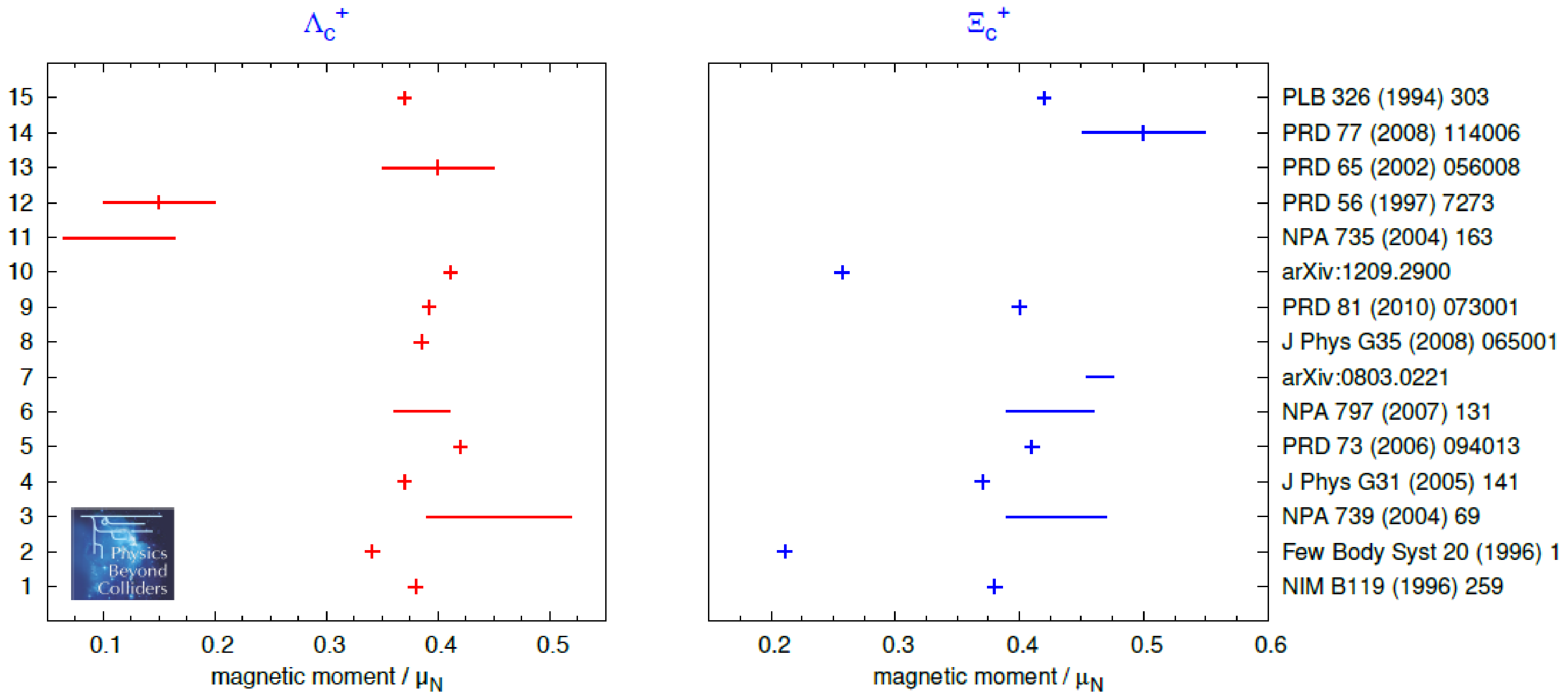
TABLE V. Contributions to the EDMs of the sextet baryons for $\Lambda = 1$ TeV. The results are given in $10^{-19}\ e$ cm and $10^{-20}\ e$ cm for the qEDM and qCEDM operators, respectively, and $10^{-21}\ e$ cm for the 4q and 4qLR operators.

Contribution	Σ_c^0	Σ_c^+	Σ_c^{++}	$\Xi_c'^0$	$\Xi_c'^+$	Ω_c^0
qEDM	$+0.06 \pm 0.86$	$+0.06 \pm 0.86$	$+0.06 \pm 0.86$	$+0.06 \pm 0.86$	$+0.06 \pm 0.86$	$+0.06 \pm 0.86$
qCEDM	$+0.10 \pm 1.37$	$+0.07 \pm 1.37$	-0.13 ± 1.51	$+0.10 \pm 1.37$	$+0.07 \pm 1.37$	$+0.10 \pm 1.37$
4q	$+0.10 \pm 2.90$	$+0.14 \pm 2.76$	$+0.28 \pm 4.17$	-0.10 ± 2.32	-0.13 ± 2.72	$+0.19 \pm 2.99$
4qLR	$+0.01 \pm 0.49$	$+0.02 \pm 1.37$	$+0.04 \pm 1.10$	$+0.03 \pm 1.33$	-0.14 ± 1.58	$+0.13 \pm 2.31$

Baryon MDM

- MDMs can test **QCD theory**
- Charmed baryon MDM?

CERN-PBC-REPORT-2018-008



A measurement of μ_{Λ_c} and μ_{Ξ_c} at 10% precision would be useful to confront with theory predictions

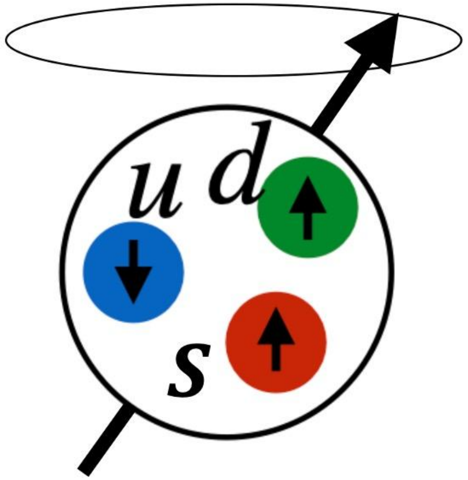
Experimental measurement of MEDM

- EDM and MDM extracted from spin procession in EM field

$$\frac{d\boldsymbol{s}}{dt} = \boldsymbol{s}\times(\boldsymbol{\Omega}_{\mathrm{MDM}} + \boldsymbol{\Omega}_{\mathrm{EDM}} + \boldsymbol{\Omega}_{\mathrm{TH}})$$

$$\boldsymbol{\Omega}_{\mathrm{MDM}} = \frac{g\mu_B}{\hbar}\left(\mathbf{B} - \frac{\gamma}{\gamma+1}(\boldsymbol{\beta}\cdot\mathbf{B})\boldsymbol{\beta} - \boldsymbol{\beta}\times\mathbf{E}\right)$$

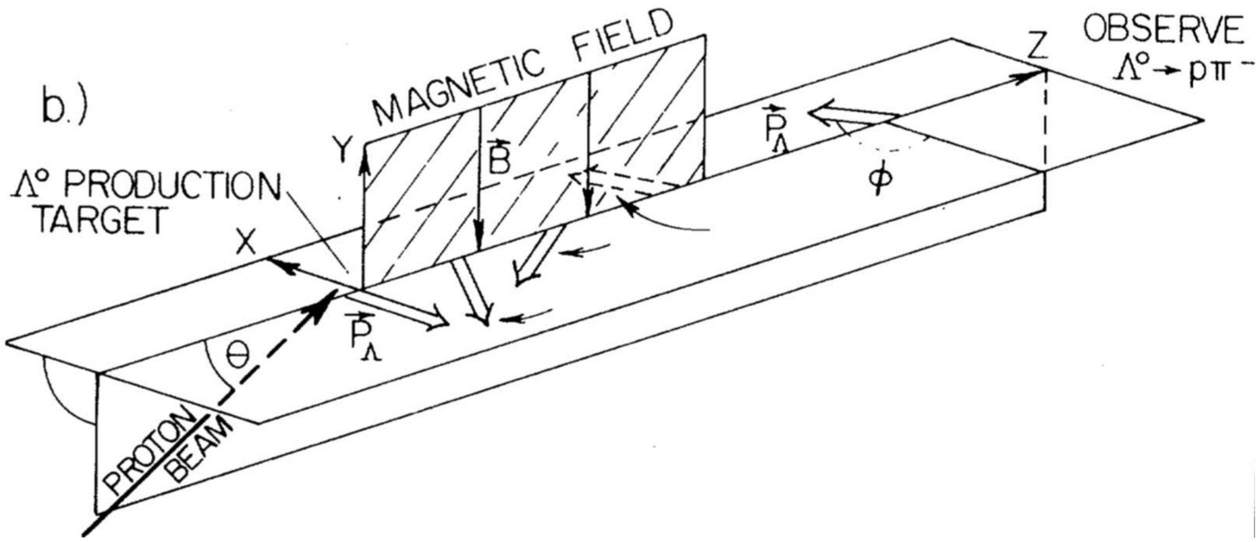
$$\boldsymbol{\Omega}_{\mathrm{EDM}} = \frac{d\mu_B}{\hbar}\left(\mathbf{E} - \frac{\gamma}{\gamma+1}(\boldsymbol{\beta}\cdot\mathbf{E})\boldsymbol{\beta} - \boldsymbol{\beta}\times\mathbf{B}\right)$$



- Experimental requirement:
  - ✓ Sizable **polarized** particle source
  - ✓ **Excellent detector** for polarization measurement via angular analysis
  - ✓ **Enough fight length/intense** EM field for precession

Significant challenge for short-lived particles, i.e. $\Lambda(10^{-10}s), \Lambda_c^0(10^{-13}\ s), \Sigma^0(10^{-20}s)$

Experimental techniques



Phys. Rev. D23 (1981) 814

$d_\Lambda < 1.5\times10^{-16} e$ cm @ 95% CL

Phys. Rev. Lett. 41 (1978) 1348

$\mu_\Lambda = (-0.613 \pm 0.004)\mu_N$

- Last direct measurement in 80's @Fermilab
- Fixed-target experiment with 300GeV proton beam on Be
- Magnet: 5m, 15Tm
- Reconstructed 3×10^6 $\Lambda \to p\pi^-$ decays
- Small transverse polarization ~8%

sensitivity depend on polarization
and difficult to improve to 10^{-18} e cm

New techniques at BEPCII&BESIII

PHYSICAL REVIEW D VOLUME 47, NUMBER 5 1 MARCH 1993

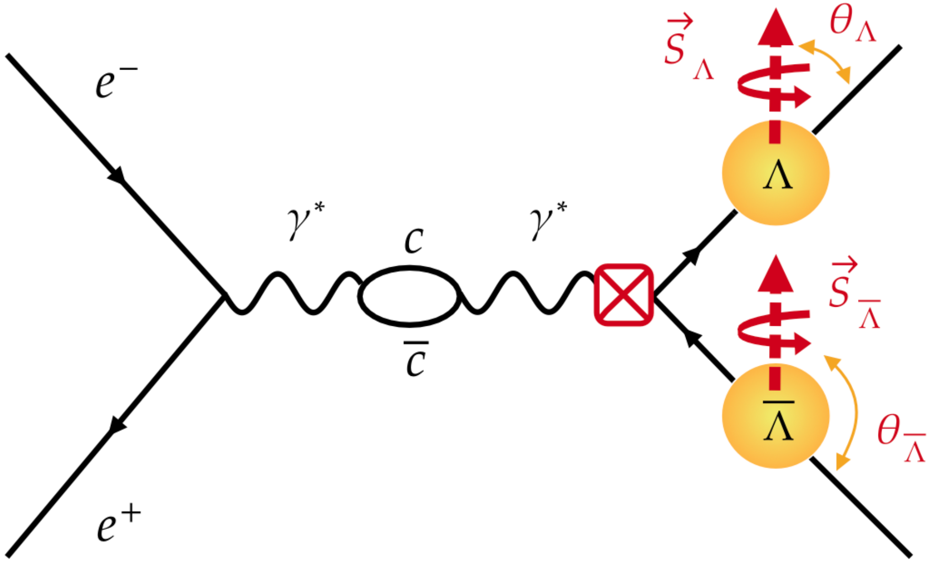
CP violation in $J/\psi \rightarrow \Lambda\bar{\Lambda}$

Xiao-Gang He, J. P. Ma, and Bruce McKellar

Research Center for High Energy Physics, School of Physics, University of Melbourne, Parkville, Victoria 3052 Australia

(Received 19 November 1992)

We study CP violation in $J/\psi \rightarrow \Lambda\bar{\Lambda}$ decay. This decay provides a good place to look for CP violation. Some observables are very sensitive to the Λ electric dipole moment d_Λ and therefore can be used to improve the experimental upper bound on d_Λ. CP violations in the lepton pair decays of J/ψ and Υ are also discussed.



$$L_{c-\Lambda} = -\frac{2}{3M^2} e d_\Lambda (p_1^\mu - p_2^\mu)\bar{c}\gamma_\mu c \bar{\Lambda} i\gamma_5 \Lambda$$

$$H_T = \frac{2e}{3M^2} g_V d_\Lambda$$

measure time-like dipole form factor with $q = m_{J/\psi}$

X.G.He, J.P. Ma, Phys.Rev.D47(1993)1744

X.G.He, J.P. Ma, Phys.Lett.B 839(2023)137834

New techniques at BEPCII&BESIII

arXiv:2506.19180
Accepted by Science

- 3M $J/\psi \to \Lambda\bar{\Lambda}$ decays reconstructed with purity > 99%, similar statistics as Fermilab in 1980s
- Preserve CP symmetry and a 3-order-of-magnitude improvement

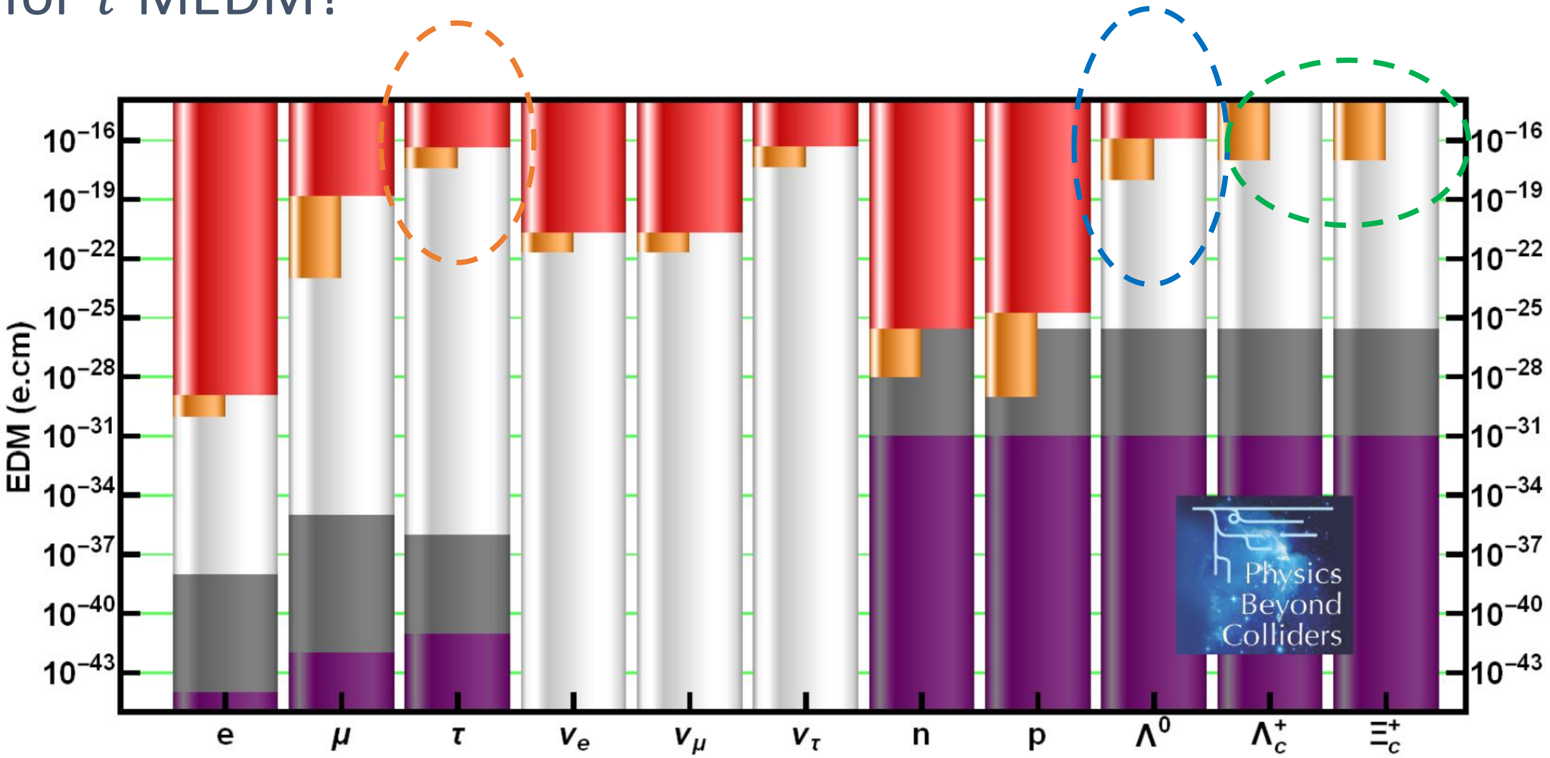
$$Re(d_\Lambda) = (-3.1 \pm 3.2 \pm 0.5) \times 10^{-19}\ e\ \text{cm},$$
$$Im(d_\Lambda) = (2.9 \pm 2.6 \pm 0.6) \times 10^{-19}\ e\ \text{cm}.$$

$$-8.6 \times 10^{-19} < Re(d_\Lambda) < 3.3 \times 10^{-19}\ e\ \text{cm},$$
$$-2.5 \times 10^{-19} < Im(d_\Lambda) < 7.2 \times 10^{-19}\ e\ \text{cm},$$
$$|d_\Lambda| < 6.5 \times 10^{-19}\ e\ \text{cm}.$$

Parameter	This measurement
α_Λ	$0.7524 \pm 0.0036 \pm 0.0008$
$\alpha_{\bar{\Lambda}}$	$-0.7571 \pm 0.0036 \pm 0.0008$
$Re(G_2)$	$(9.71 \pm 0.06 \pm 0.24) \times 10^{-4}$
$Im(G_2)$	$(9.14 \pm 0.04 \pm 0.23) \times 10^{-4}$
P_L	$(-1.8 \pm 1.2 \pm 0.8) \times 10^{-3}$
$Re(F_A)$	$(-2.4 \pm 1.6 \pm 3.1) \times 10^{-6}$
$Im(F_A)$	$(-7.9 \pm 3.7 \pm 2.5) \times 10^{-6}$
$Re(H_T)$	$(-1.4 \pm 1.4 \pm 0.2) \times 10^{-6}\ \text{GeV}^{-1}$
$Im(H_T)$	$(1.3 \pm 1.2 \pm 0.4) \times 10^{-6}\ \text{GeV}^{-1}$
$\alpha_{J/\psi}$	$0.4748 \pm 0.0022 \pm 0.0017$
$\Delta\phi$	$0.7552 \pm 0.0042 \pm 0.0013$
A_{CP}	$(-3.1 \pm 4.6 \pm 1.1) \times 10^{-3}$
$\sin^2\theta_W^{\text{eff}}$	$-0.15 \pm 0.12 \pm 0.26$
$Re(d_\Lambda)$	$(-3.1 \pm 3.2 \pm 0.5) \times 10^{-19}\ e\ \text{cm}$
$Im(d_\Lambda)$	$(2.9 \pm 2.6 \pm 0.6) \times 10^{-19}\ e\ \text{cm}$

What can be done at LHC?

- ✓ Direct measurement of hyperon MEDM?
- ✓ First attempt on charmed baryon MEDM?
- ✓ Possibility for τ MEDM?

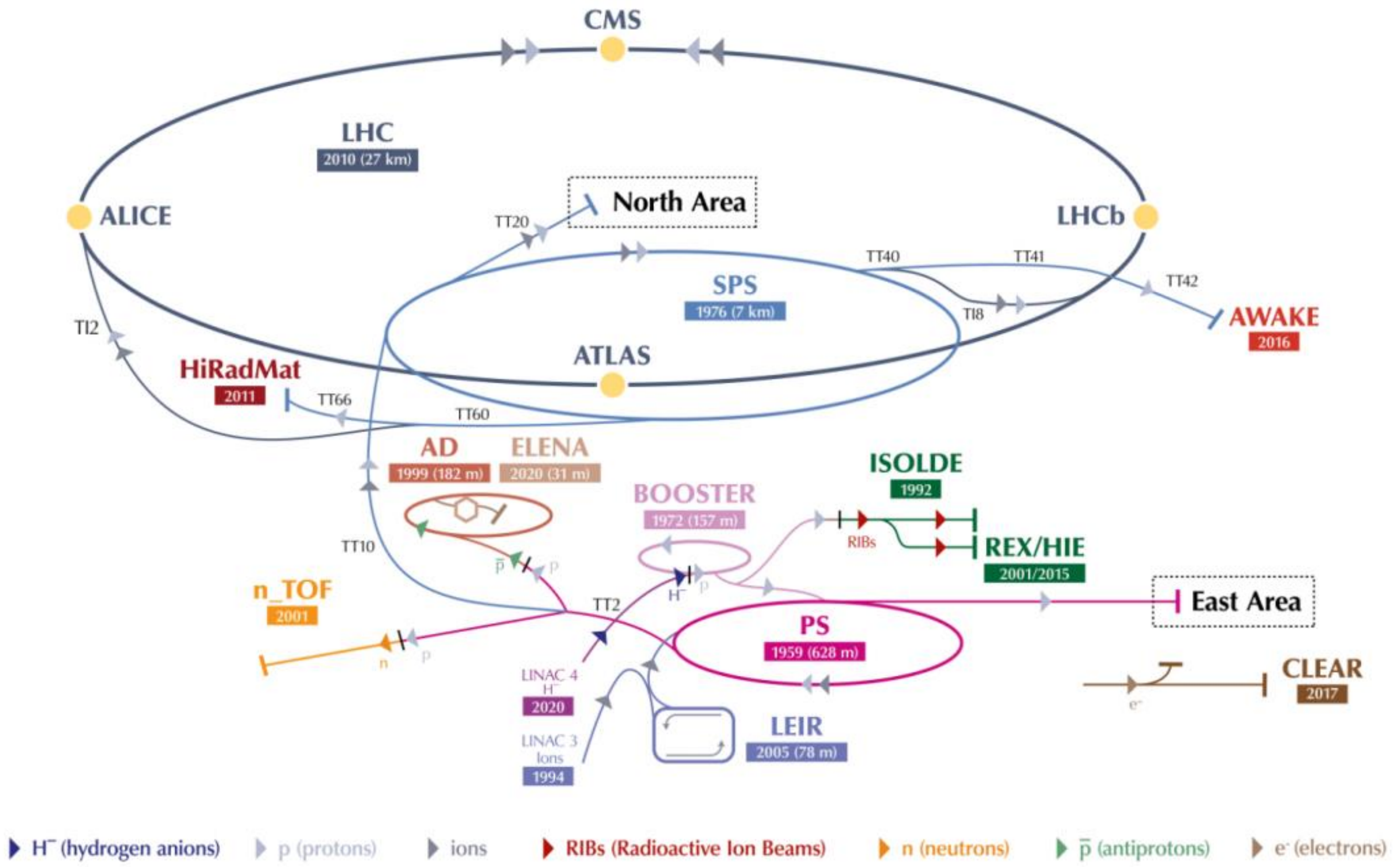


$\tau \sim 10^{-13}\ s$ $\tau \sim 10^{-10}\ s$ $\tau \sim 10^{-13}\ s$

2

Hyperon MEDM at LHCb

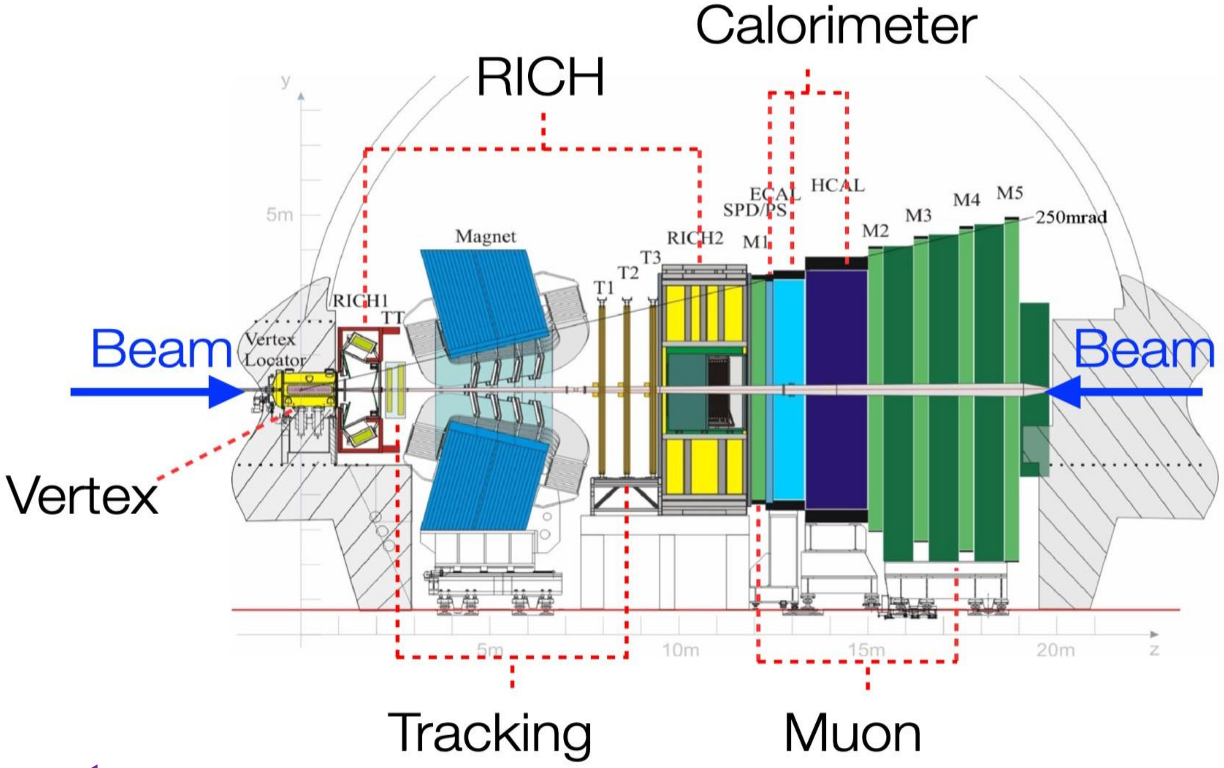
The LHCb detector

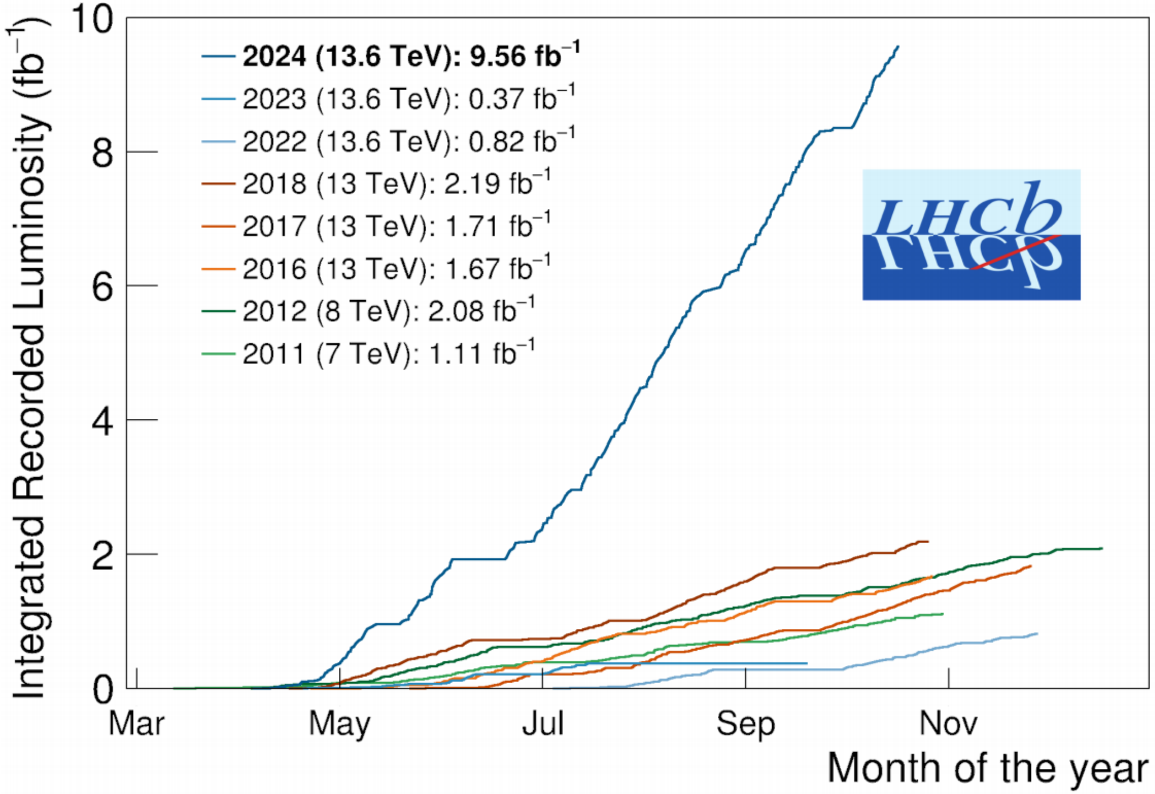


LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials

The LHCb detector

Run 1-2 detector



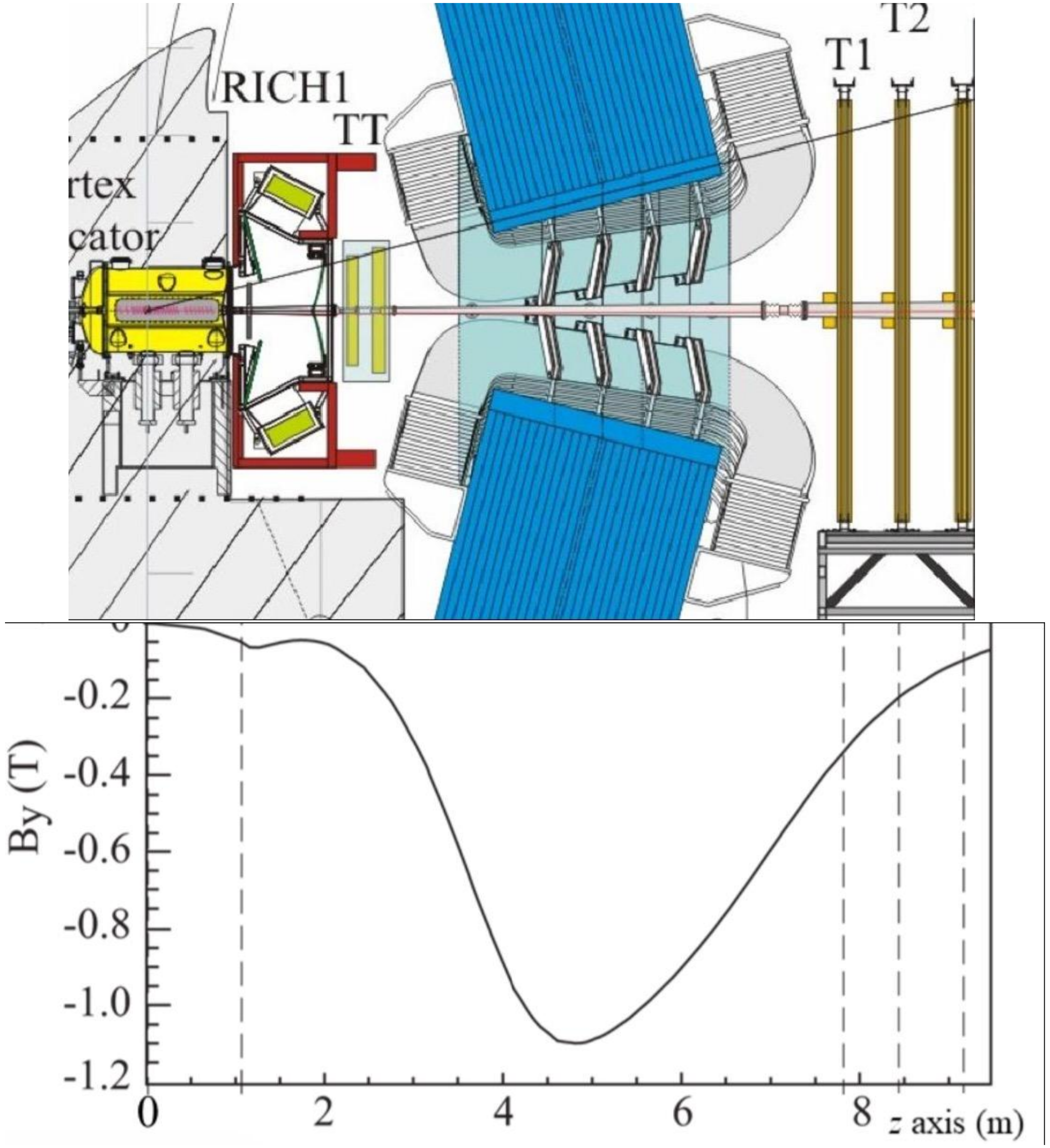


Magnet

$2 < \eta < 5$, about 25% of $b\bar{b}$ pairs inside LHCb acceptance

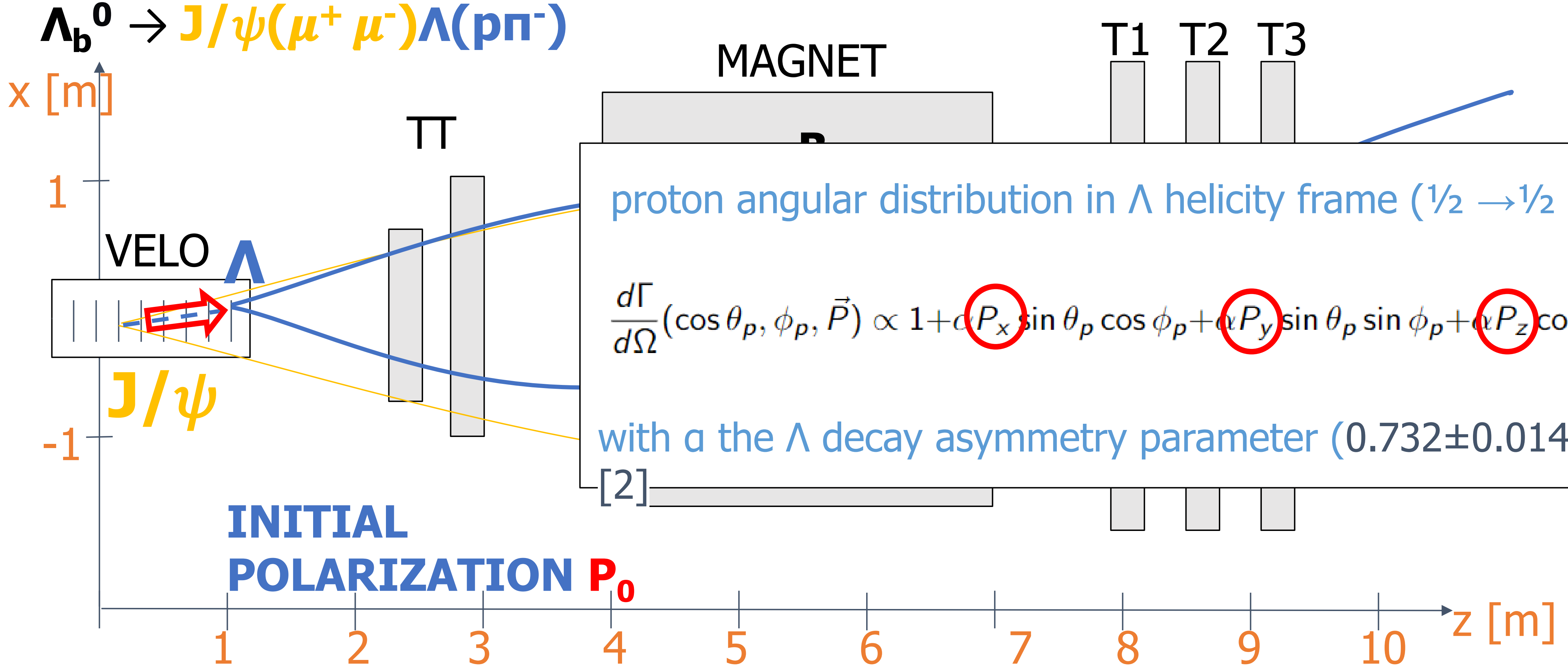
Excellent time, IP, mass resolution, and excellent tracking, PID performance.

The LHCb detector



- Acceptance:
  hor. ± 300 mrad, ver. ± 250 mrad
- Measured B field values stable within $\sigma = \pm 0.07$ gauss
- $\int Bdl = 4$ Tm

How to?



proton angular distribution in Λ helicity frame (½ →½ 0)

$$\frac{d\Gamma}{d\Omega}(\cos\theta_p, \phi_p, \vec{P}) \propto 1+\alpha P_x \sin\theta_p \cos\phi_p+\alpha P_y \sin\theta_p \sin\phi_p+\alpha P_z \cos\theta_p,$$

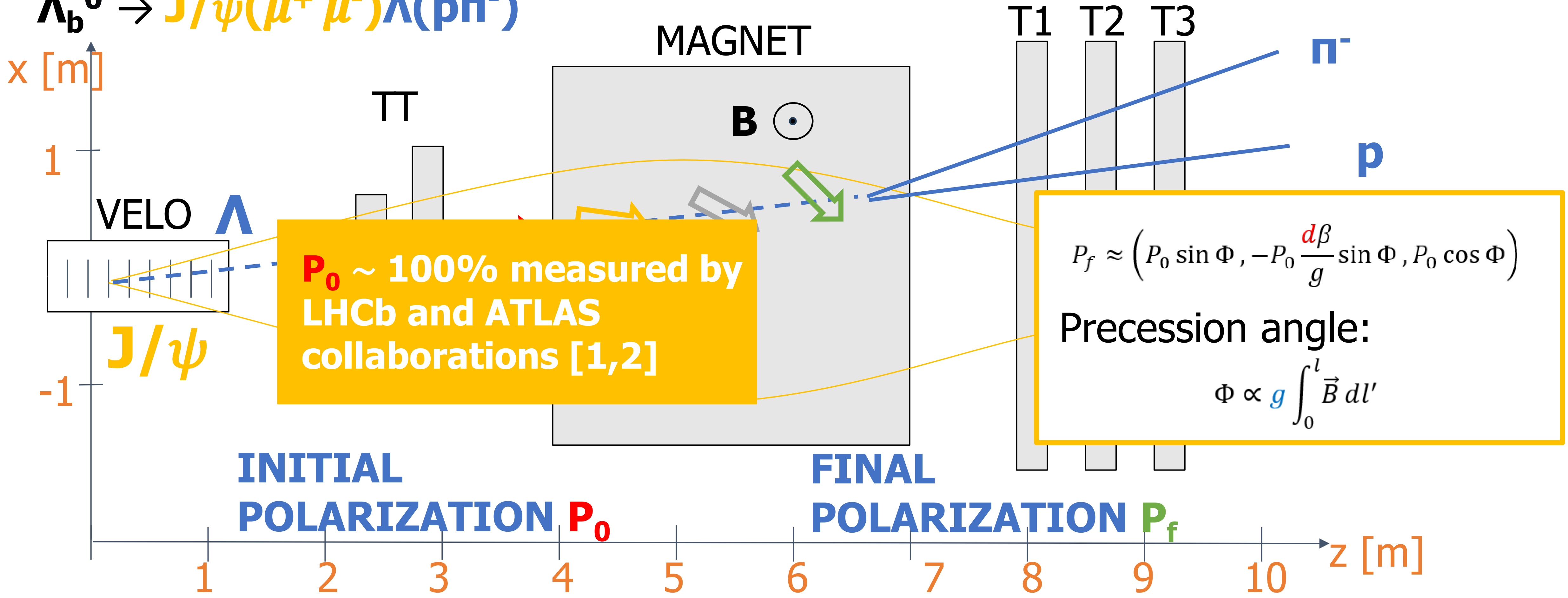
with α the Λ decay asymmetry parameter (0.732±0.014) [2]

[1] Eur. Phys. J. **C** (2017) 77:181 [2] Nature Phys. 15 (2019) 631-634

How to?

Λ polarization (helicity) precession in electromagnetic field

$\Lambda_b^0 \rightarrow J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$

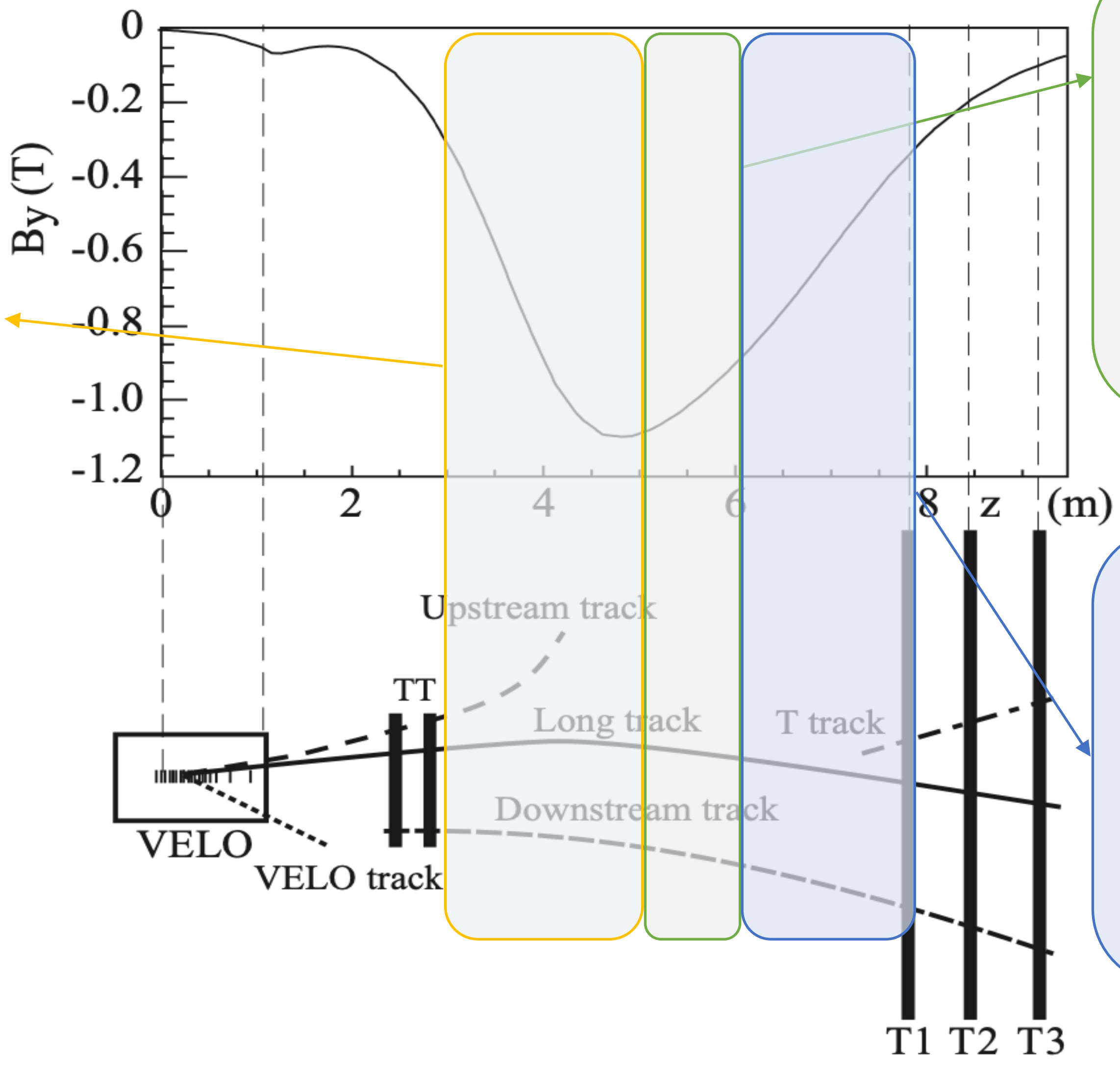


[1] Eur. Phys. J. **C** (2017) 77:181 [2] Nature Phys. 15 (2019) 631-634

Fit strategy

Region 3 < z < 5 m:

Limited precession,
Most sensitive to the
initial polarization



Region 5 < z < 6 m:

Intermediate region, adding **statistics** for both initial polarization and g and d measurements

Region 6 < z < 8 m:
Region with **maximal precession →** most sensitive to **EDM and MDM.** Poor sensitivity to the initial polarization

Fit strategy

In the **helicity** frame, $\mathbf{P_0}$ is maximal along the **Λ** momentum (~ perpendicular to **B**), the angular distribution after the precession is:

$$\frac{d\Gamma}{d\Omega}(\cos\theta_p, \phi_p, \vec{P}) \propto 1 + \alpha P_x \sin\theta_p \cos\phi_p + \alpha P_y \sin\theta_p \sin\phi_p + \alpha P_z \cos\theta_p$$

Helicity frame

Polarization after the **precession**:

$$\vec{P}(\vec{P}_0, g, d, \vec{D}, \gamma, \vec{\beta}, l) = (\vec{P}_0 \cdot \vec{\omega}')\vec{\omega}' + [\vec{P}_0 - (\vec{P}_0 \cdot \vec{\omega}')\vec{\omega}'] \cos\phi + (\vec{P}_0 \times \vec{\omega}') \sin\phi$$

Where the **precession angle** is:

$$\vec{\omega}' = \vec{\Phi}/\Phi, \quad \vec{\Phi} = \frac{\mu_B}{\beta\hbar c}\left[g\left(\vec{D} - \frac{\gamma\beta(\vec{\beta}\cdot\vec{D})}{\gamma+1}\right) + d\vec{\beta}\times\vec{D}\right]$$

Event-per-event rotation R(Φ)

Laboratory frame

and the **integrated magnetic field**:

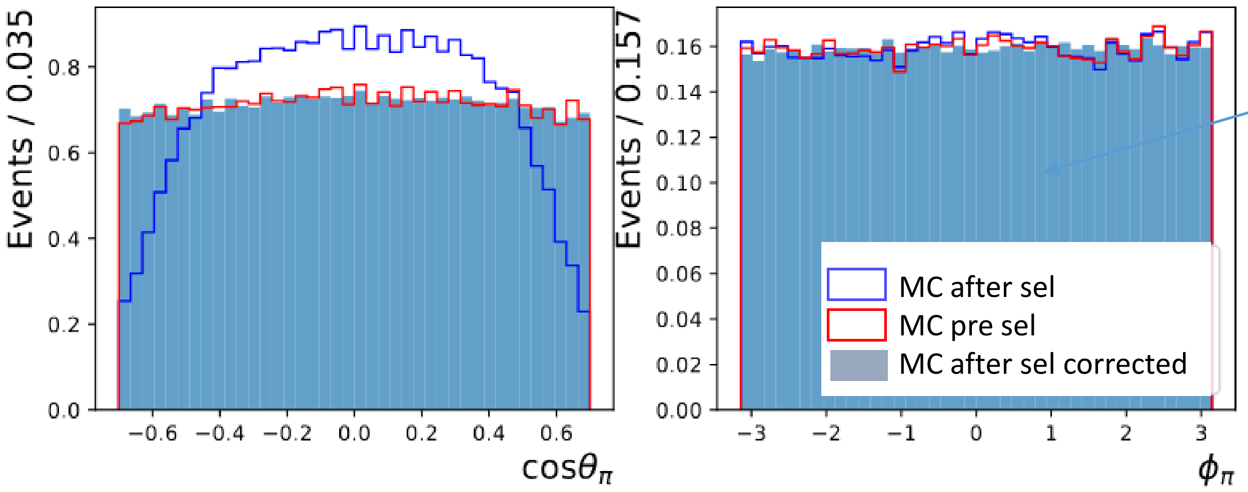
$$\vec{D} = \int \vec{B} dl$$

Variables given event-by-event to the p.d.f.
Variables to be fitted
$\mathbf{P_0}$ can be fitted or fixed

Dataset

- **Run 1 + 2 data and simulation, benchmark channels:**
  - $\Lambda_b^0 \to J/\psi(\to \mu^+\mu^-)\Lambda(\to p\pi^-)$ **(golden channel for EMDMs)**
    - **weak** production from b- and c-baryons decays → possibility to access P0~ 100%
    - **equal production of polarized Λ and $\overline{\Lambda}$ baryons (oppositely to previous experiments)**
    - **Maximum precession angle: 30°**
  - $B^0 \to J/\psi(\to \mu^+\mu^-)K_S^0(\to \pi^+\pi^-)$ **(K_S^0 null polarization → control channel for EMDMs, cross-feed background)**
- **Two body decays, with 100% initial polarization (P_0) of the Λ baryon $\sigma \propto \frac{1}{P_0\sqrt{N}}$**
- **Efficient trigger on detached $J/\psi \to \mu^+\mu^-$, already available during Run 1 and Run 2**

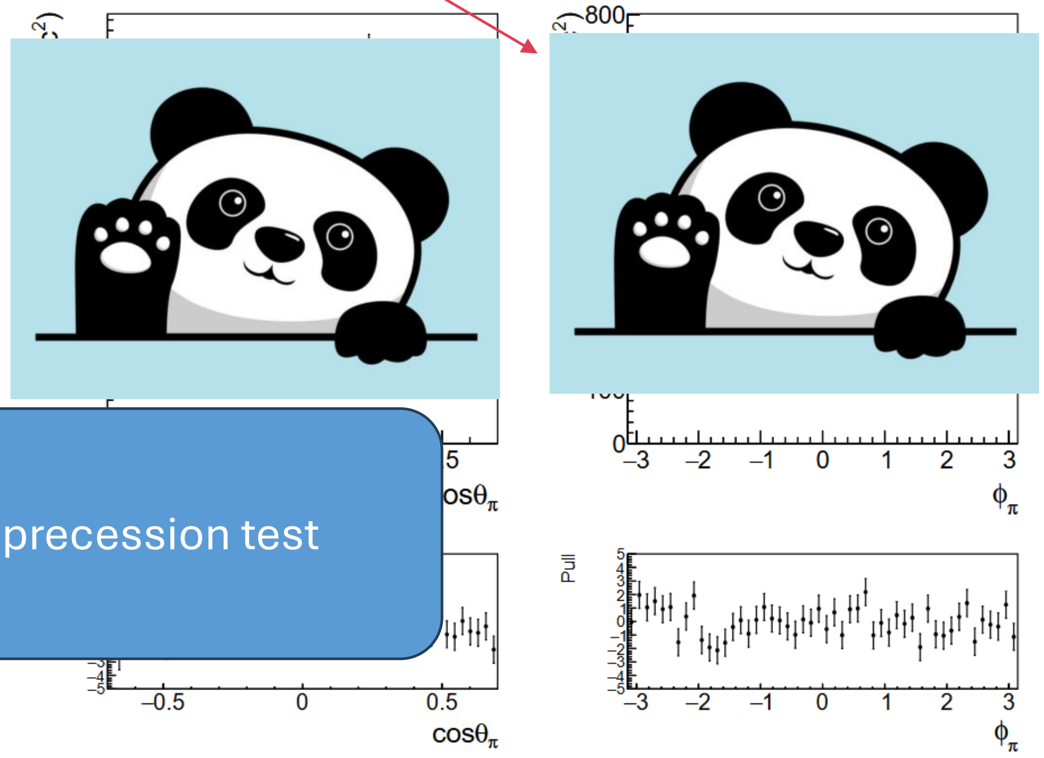
Validation with $B^0 \to J/\psi(\to \mu^+\mu^-)K_S^0(\to \pi^+\pi^-)$



Efficiency estimation on simulation (Gbreweighter trained on MC) → correction applied to data

P_{0x}	-0.006 ± 0.009
P_{0y}	0.006 ± 0.009
P_{0z}	-0.005 ± 0.010

Φ = 0, no precession test

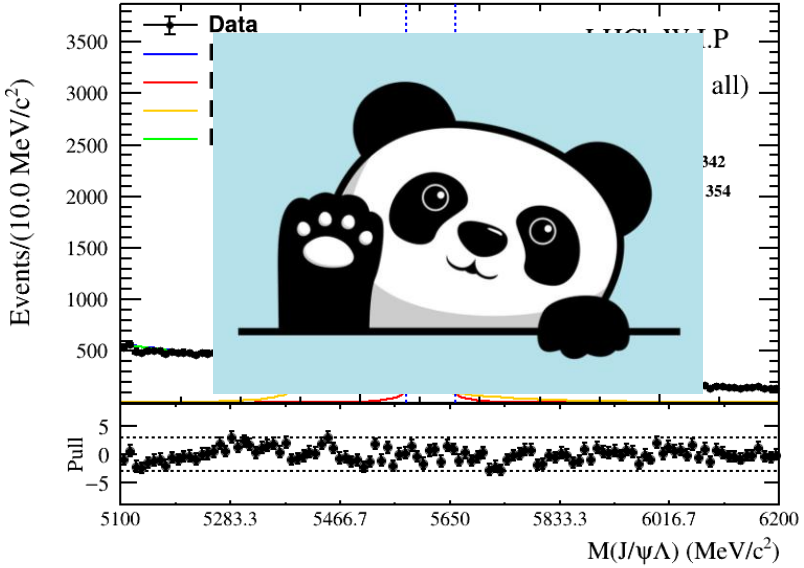


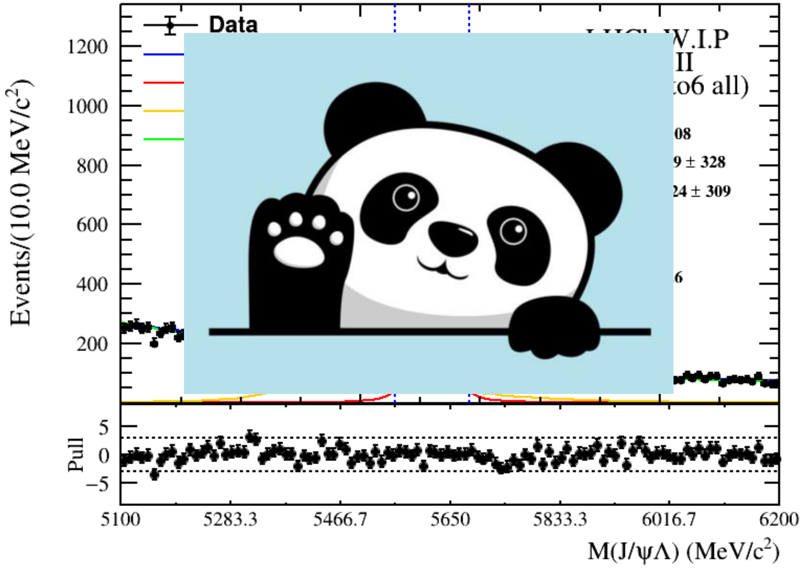
Background subtracted data distributions.

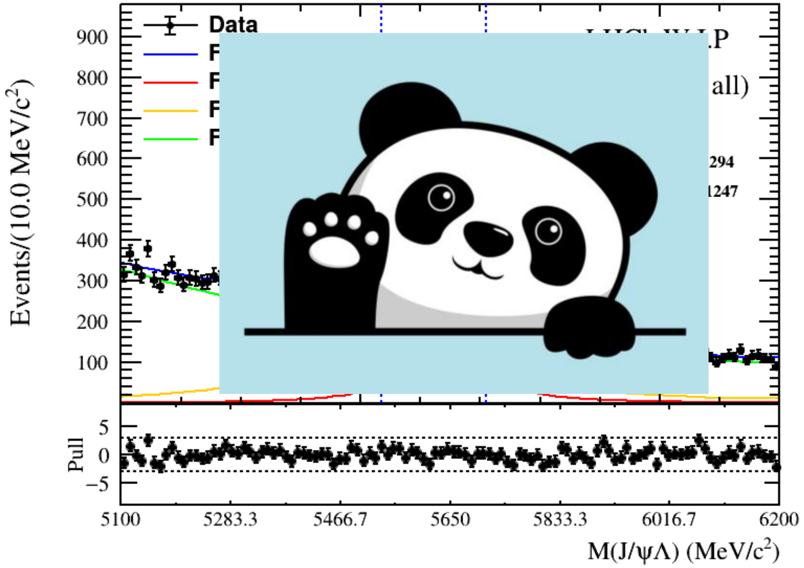
Result compatible with **zero on data**, as expected! **It validates the fitting procedure** (not the precession part).

Signal yield of $\Lambda_b^0 \to \Lambda J/\psi$

As expected from simulation, the resolution on the invariant mass improves with the decreasing of z: larger lever arm → better momentum resolution → better mass resolution

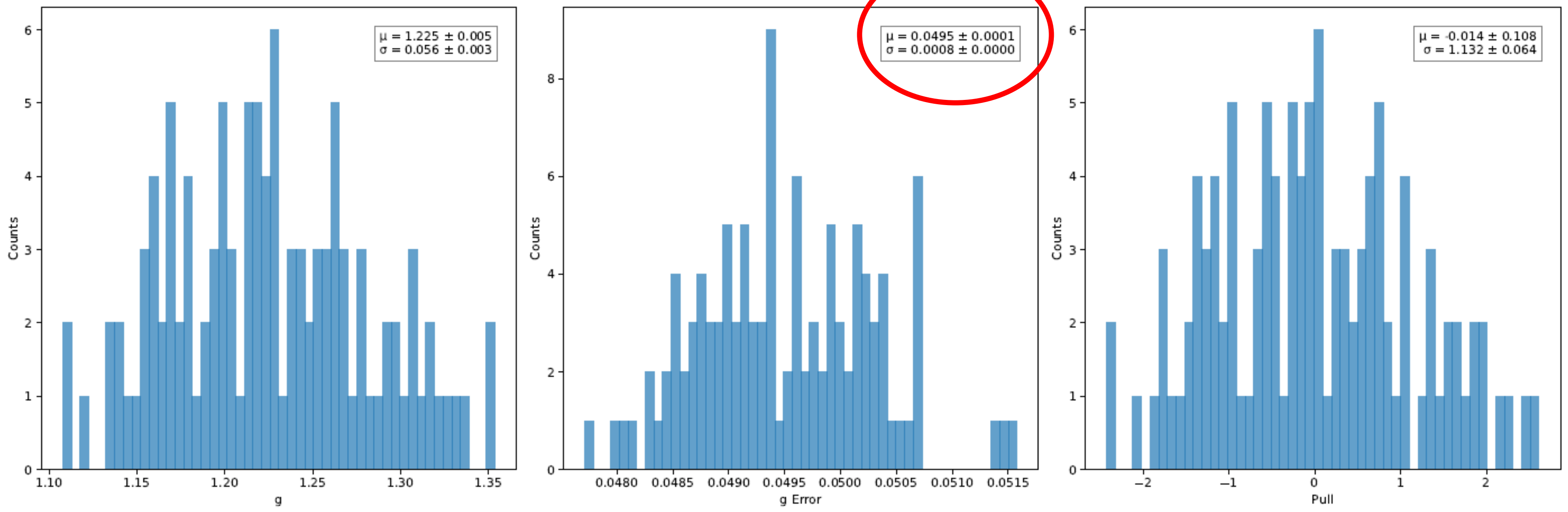






	$\mathrm{EndVz} \in (3,5)$ m	$\mathrm{EndVz} \in (5,6)$ m	$\mathrm{EndVz} \in (6,8.5)$ m
n_{sig} within 3σ	7978 ± 121	3873 ± 101	3632 ± 183
Purity within 3σ	71%	61%	46%

Pseudo-experiments



110 pseudo-experiments with 25k events (as in Run 1 + Run 2 data) of $\Lambda_b^0 \rightarrow \Lambda(\rightarrow p\pi^-)J/\psi(\rightarrow \mu^+\mu^-)$ decays each, **3 < z < 8 m**

$\sigma_d \sim 0.0495$ → $d_\Lambda \sim 4.4 \times 10^{-16}\, e$ cm
Fermilab experiment: $1.5 \times 10^{-16}\, e$ cm

$\sigma_g / g \sim 0.04$
Fermilab experiment: $\sigma_g / g \sim 0.008$

→Factor 3/5 worse for now, but more data are coming…

Other possibilities in Run3

Run 3: 2022-2026, expected **20 fb-1**

New **fully software trigger**, development of dedicated trigger lines for all the decays with T tracks:

- ✓ $\Lambda_b^0 \to \Lambda J/\psi$ (produced $N_\Lambda = 1.2 \times 10^6$ /fb^{-1})
- ✓ $B^0 \to J/\psi(\to \Lambda\bar{\Lambda})K_S^0(\to \pi^+\pi^-)$

Table 1: Dominant Λ production mechanisms from heavy baryon decays and estimated yields produced per fb^{-1} at $\sqrt{s} = 13$ TeV, shown separately for SL and LL topologies. The Λ baryons from Ξ^- decays, produced promptly in the pp collisions, are given in terms of the unmeasured production cross section.

SL events	N_Λ/ fb^{-1} ($\times 10^{10}$)	LL events, $\Xi^- \to \Lambda\pi^-$	N_Λ/ fb^{-1} ($\times 10^{10}$)
$\Xi_c^0 \to \Lambda K^-\pi^+$	7.7	$\Xi_c^0 \to \Xi^-\pi^+\pi^+\pi^-$	23.6
$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	3.3	$\Xi_c^0 \to \Xi^-\pi^+$	7.1
$\Xi_c^+ \to \Lambda K^-\pi^+\pi^+$	2.0	$\Xi_c^+ \to \Xi^-\pi^+\pi^+$	6.1
$\Lambda_c^+ \to \Lambda\pi^+$	1.3	$\Lambda_c^+ \to \Xi^- K^+\pi^+$	0.6
$\Xi_c^0 \to \Lambda K^+K^-$ (no ϕ)	0.2	$\Xi_c^0 \to \Xi^- K^+$	0.2
$\Xi_c^0 \to \Lambda\phi(K^+K^-)$	0.1	Prompt Ξ^-	$0.13 \times \sigma_{pp\to\Xi^-}$ [μb]

- ✓ $\Xi_c^0 \to \Xi^-\pi^+, \Xi^- \to \Lambda\pi^-$
- ✓ $\Xi_c^0 \to \Xi^-\pi^-\pi^+\pi^+$
- ✓ $\Xi_c^0 \to \Lambda K^-\pi^+$
- ✓ $\Lambda_c^+ \to \Lambda\pi^-\pi^+\pi^+$
- ✓ $\Xi_c^+ \to \Lambda K^-\pi^+\pi^+$
- ✓ $\Xi_c^+ \to \Xi^-\pi^+\pi^+$

→

Charm decays: number of **Λ** produced is some (2-5) orders of magnitude greater than that in b decays. Trigger lines working in Run 3

Future upgrade

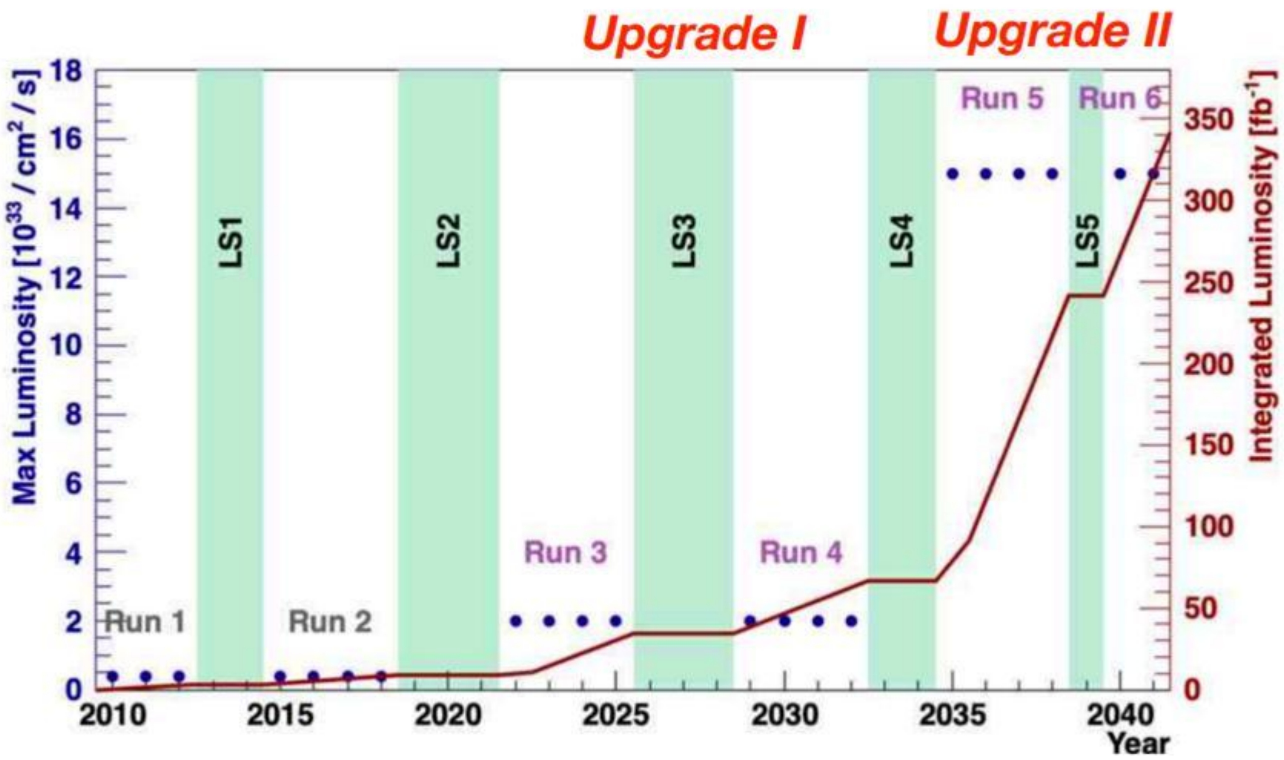
Current limit Λ EDM: Fermilab, 1981, fixed target experiment **Λ EDM $< 1.5 \times 10^{-16}\ e\ cm$**, with 95% C.L.

Run 1 + 2: analysis to obtain a very first measurement of EDM and MDM at a collider experiment: proof of principle. First measurement of $\bar{\Lambda}$ MDM.

Run 1 + Run 2 + Run 3: similar sensitivity to the current limits (with the 2 decays considered, large room for improvements with other decays not yet analyzed).

Run 1 + Run 2 + Run 3 + Run 4: sensitivity reachable of $\sigma_\delta \approx 1.3 \times 10^{-18}\ e\ cm$ ($50\ \text{fb}^{-1}$ data)

LHCb plans to run up to 2041 and reach $300\ \text{fb}^{-1}$ data $\Rightarrow$ $\sigma_\delta \approx 5 \times 10^{-19}\ e\ cm$ on a long timescale



Current measured value Λ MDM: $\boldsymbol{\mu = 0.613 \pm 0.004 \mu_N}$

Expected improvement Λ MDM: sensitivity reachable $\sigma_\mu \sim 10^{-4}\mu_N$ with 50 fb-1 data $\Rightarrow$ first **CPT** test at 10^{-4} **level** with Λ baryons

3

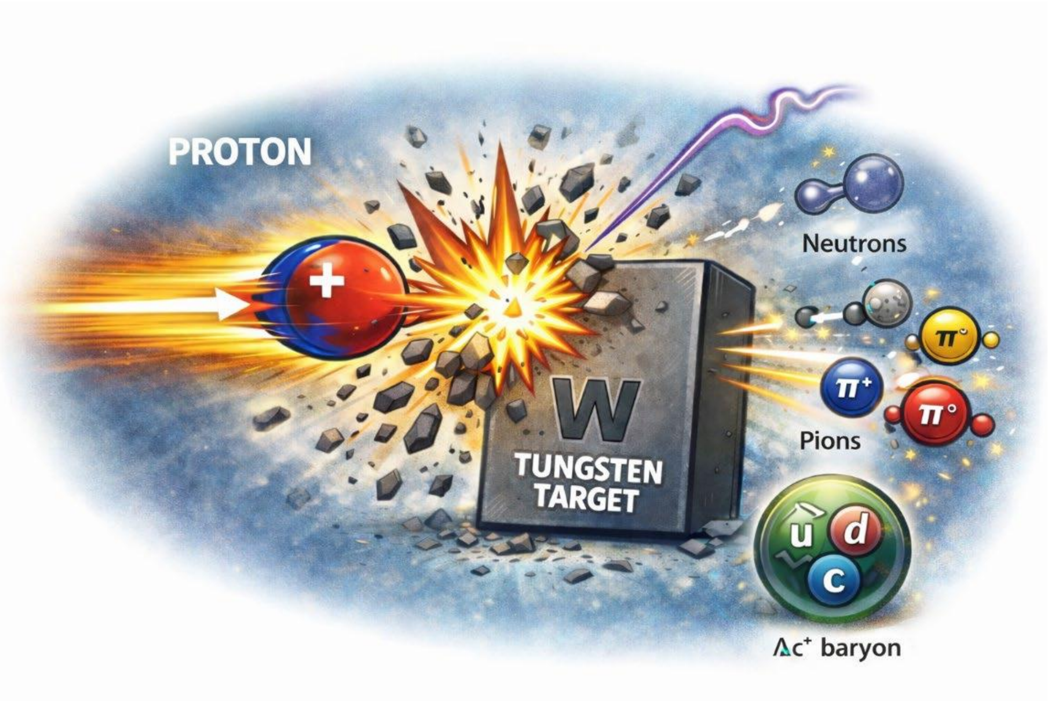
Charmed baryon MEDM at ALADDIN

The difficulties

- MDM and EDM accessed through spin precession in EM field
- Requirements & challenges:
  - Charm baryon lifetimes are very short, $\tau \approx 2 - 4 \times 10^{-13}\ s$

    ⇒ large enough **flight length** ≈ 7−10 cm ⇒ **ultra-relativistic baryons**, $\gamma \approx 1000$

    ⇒ very **strong EM field,** $B_{\text{eff}} \approx 500\ \text{T}$
  - **High intensity beam of polarized** charm baryons
  - **Forward spectrometer** for signal reconstruction, background rejection and angular analysis (analyzing power)
- Charm baryons from fixed target-target **pW collisions** at the LHC, $\sqrt{s} = 115\ \text{GeV}$ (7 TeV proton beam)
- And the EM field?



Spin precession inside a crystal

V. M. Biryukov et al., Springer-Verlag Berlin Heidelberg, 1997

To measure EDM and MDM of short-lifetime particles (~5cm) strong EM field are needed.

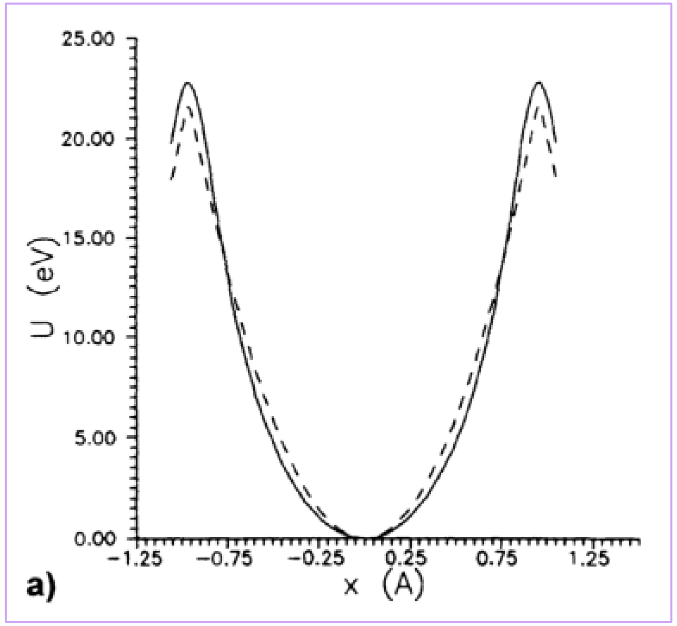
In bent crystal we obtain:

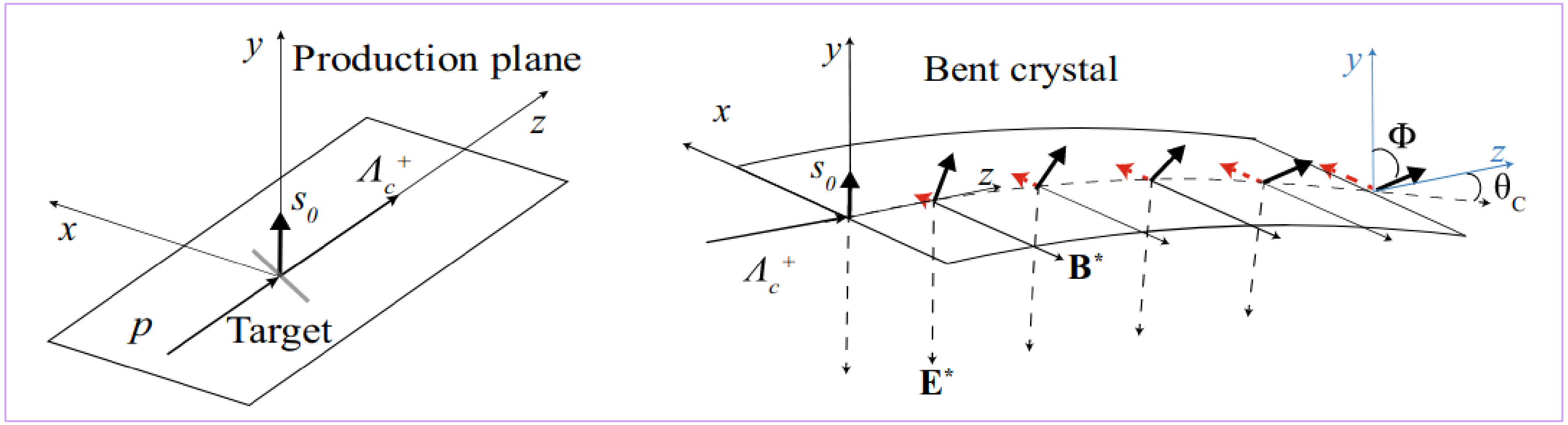
- Electric field E ≈ 1 GV/cm
- Effective magnetic field B ≈ 500 T

Positively charged particles are **channeled** between the atomic planes if their impact angle is small enough.

- ✓ Steer the particle trajectories of a given angle.
- ✓ Induce a **spin precession** of the particles in a short distance

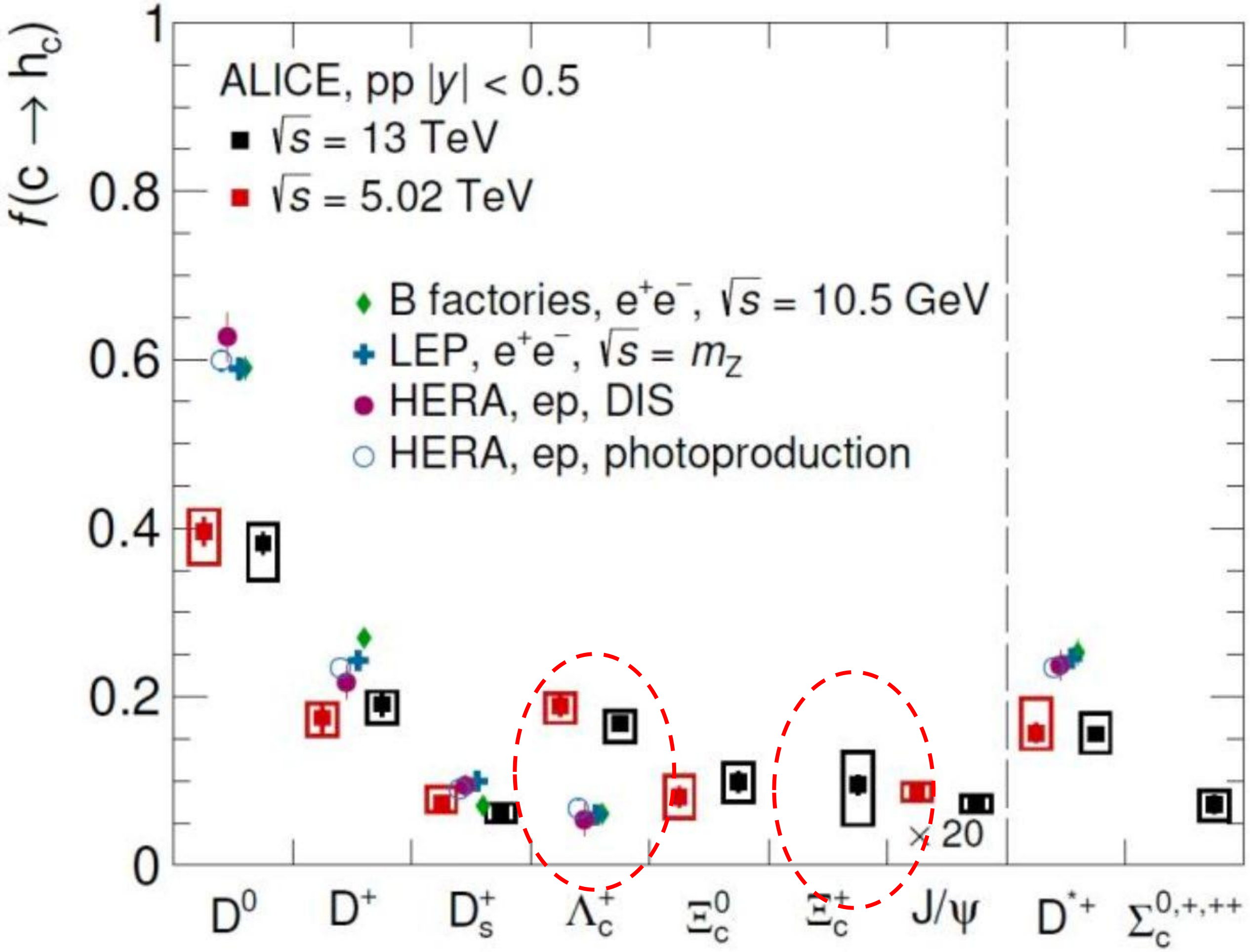
$$\Phi \approx \frac{g-2}{2}\gamma\theta_C \qquad \mathbf{s} = \begin{cases} s_x \approx s_0 \dfrac{d}{g-2}(\cos\Phi - 1) \\ s_y \approx s_0 \cos\Phi \\ s_z \approx s_0 \sin\Phi \end{cases}$$





Charm fragmentation fractions

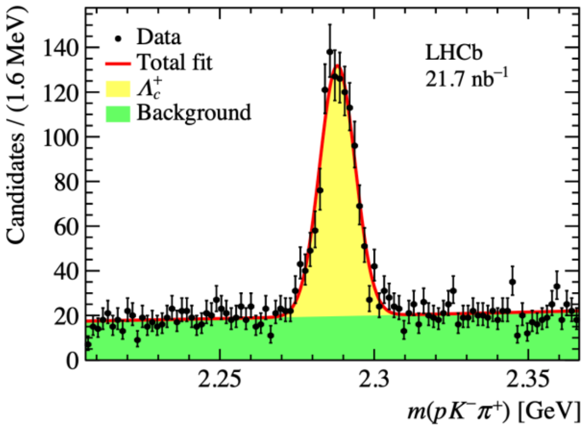
- Charm **fragmentation fractions** recently measured by ALICE are not in agreement with previous measurements from e^+e^-, e^-p, pp data
- Points to an increase of charm baryon fragmentation fractions with lower p_T
- New measurements ongoing with LHCb SMOG(2) at similar $\sqrt{s}$ and low p_T

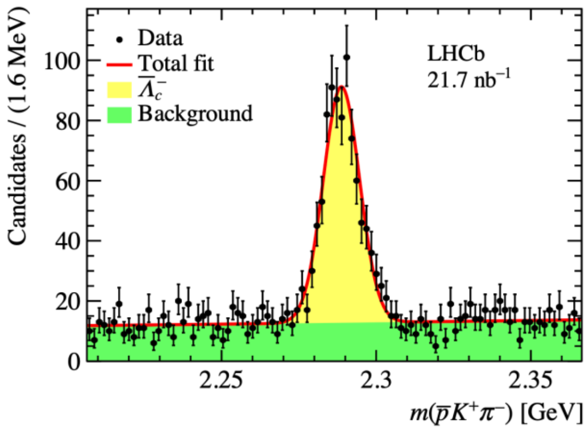


PRD 105 (2022) L011103
JHEP 12 (2023) 086
arXiv:2405.14571

Polarization in p-Ne collisions with LHCb SMOG

- Polarization of Λ_c^+ at $\sqrt{s} = 115$ GeV is unknown
- Measurement of Λ_c^+ polarization at LHCb SMOG p-Ne collision at $\sqrt{s} = 68.6$ GeV (different energy from ALADDIN case)
- **First differential measurement** of Λ_c^+ and $\overline{\Lambda}_c^-$ polarization as a function of x_F and p_T. Interesting to understand polarization mechanism in strong production



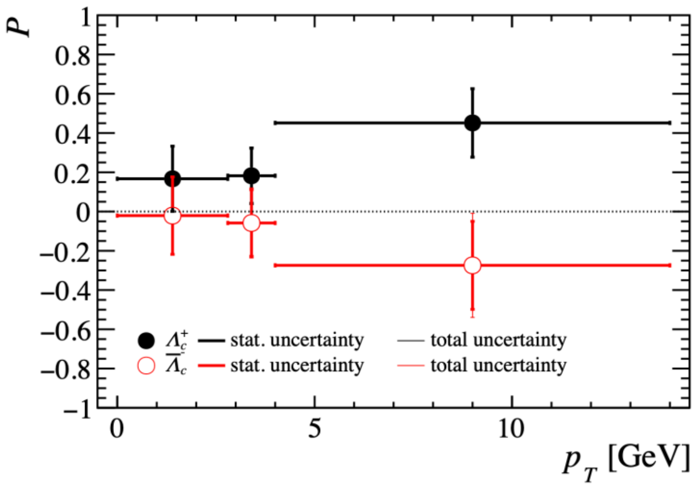


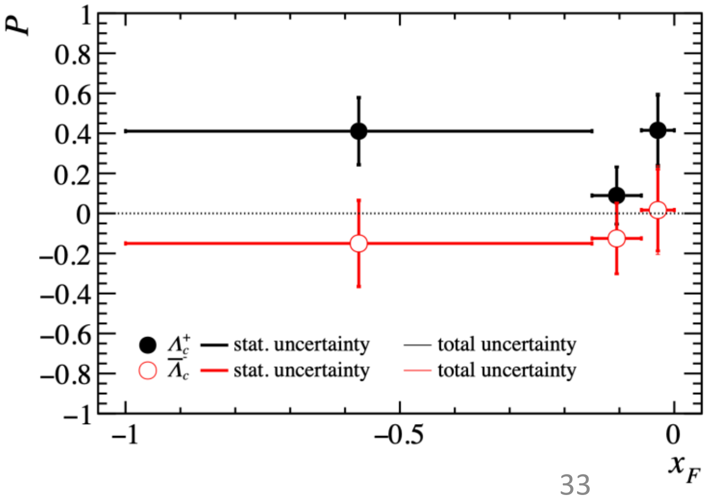
$N_{\Lambda_c^+} \approx 910$

$N_{\overline{\Lambda}_c^-} \approx 710$

$P_{\Lambda_c^+} = (24.4 \pm 9.5\,(\text{stat}) \pm 2.2\,(\text{syst}))\%,$

$P_{\overline{\Lambda}_c^-} = (-8 \pm 12\,(\text{stat}) \pm 3\,(\text{syst}))\%,$



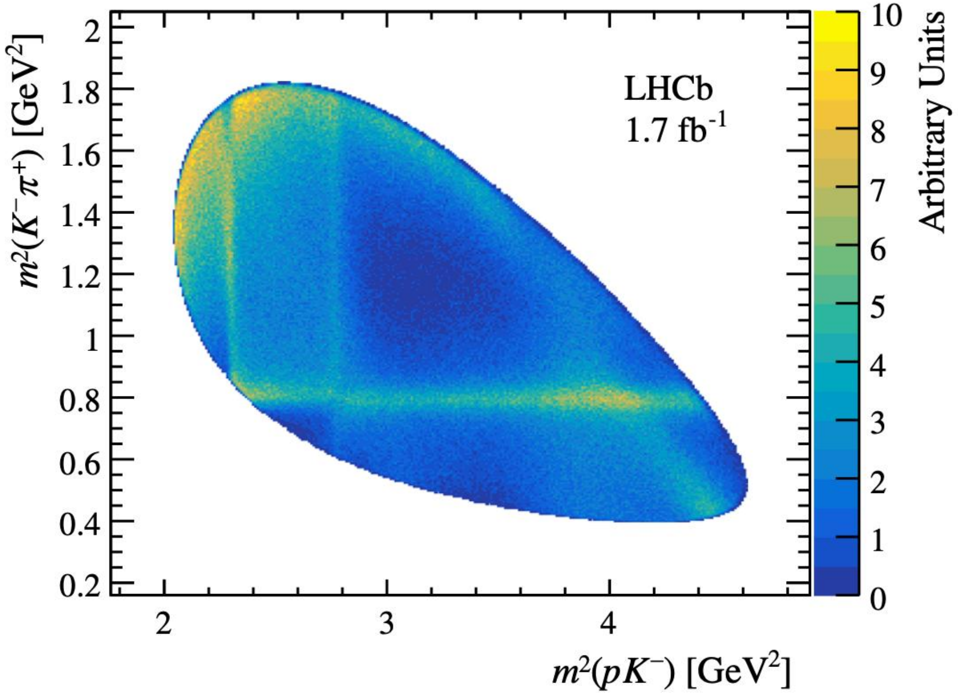


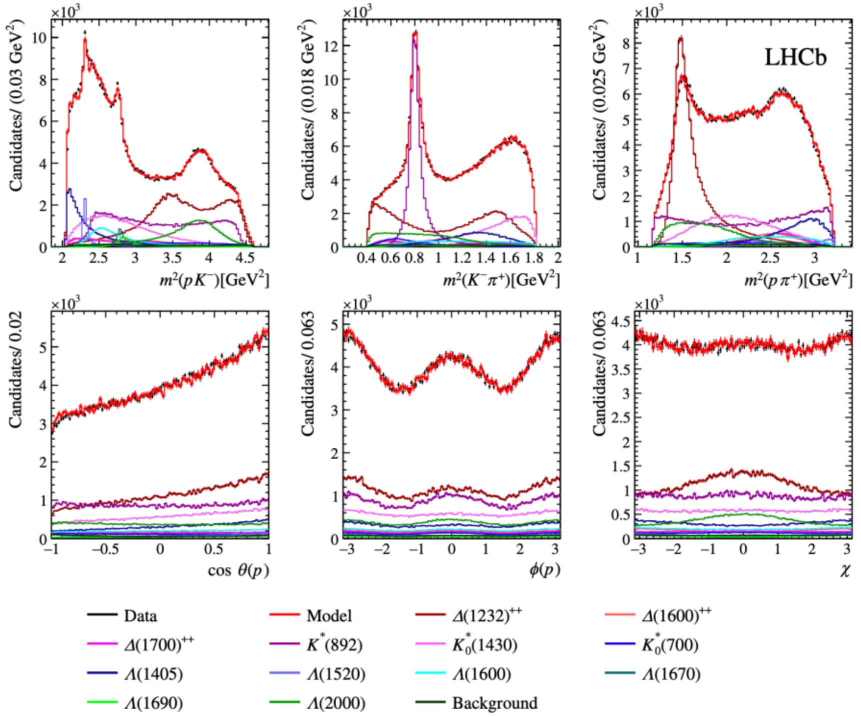
CERN-EP-2026-016, arXiv:2602.17184 (accepted by PRL)

Amplitude analysis at LHCb

PHYS. REV. D 108, 012023 (2023)

Use 400k $\Lambda_c^+ \to pK^-\pi^+$ signal events from semi-leptonic beauty hadron decays to determine the **amplitude model and Λ_c^+ polarization**



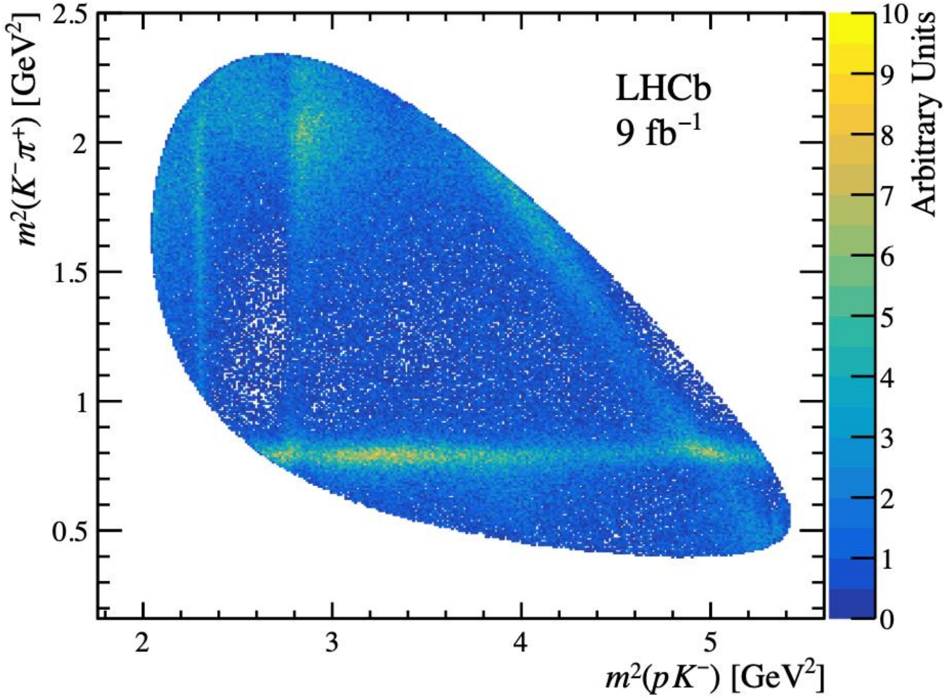


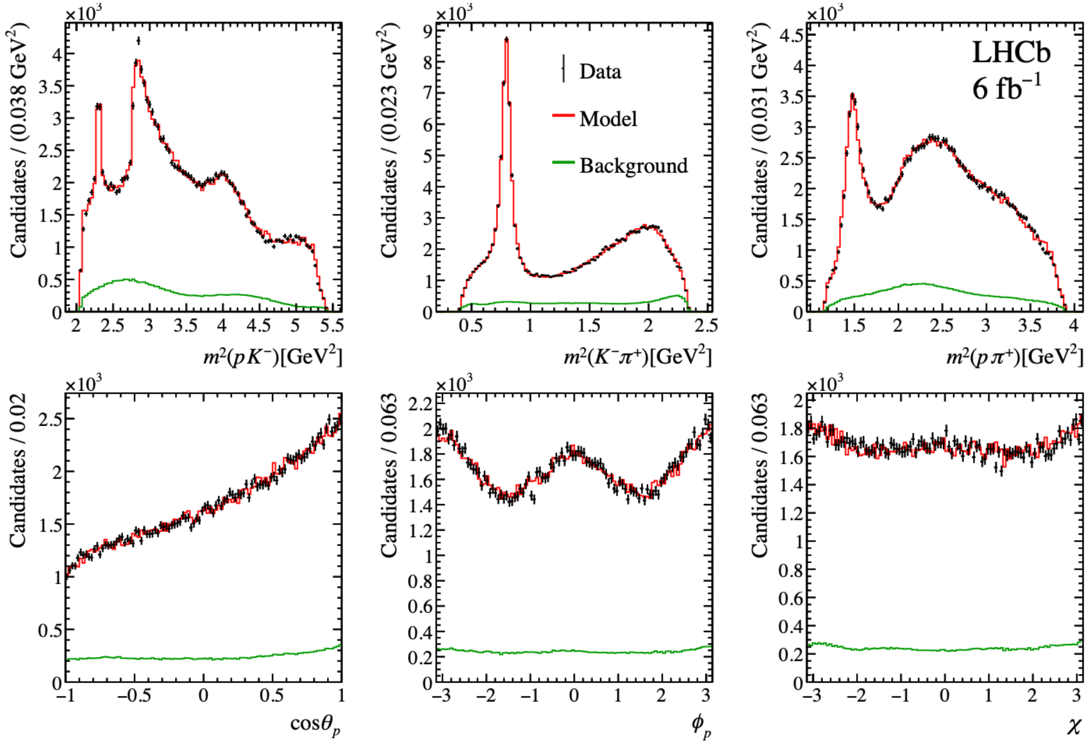
Large sensitivity to polarization (analyzing power). **$\Lambda_c^+ \to pK^-\pi^+$ best probe for Λ_c^+ polarization measurements** of produced in fixed-target collisions

Amplitude analysis at LHCb

PHYS. REV. D 112, 092003 (2025)

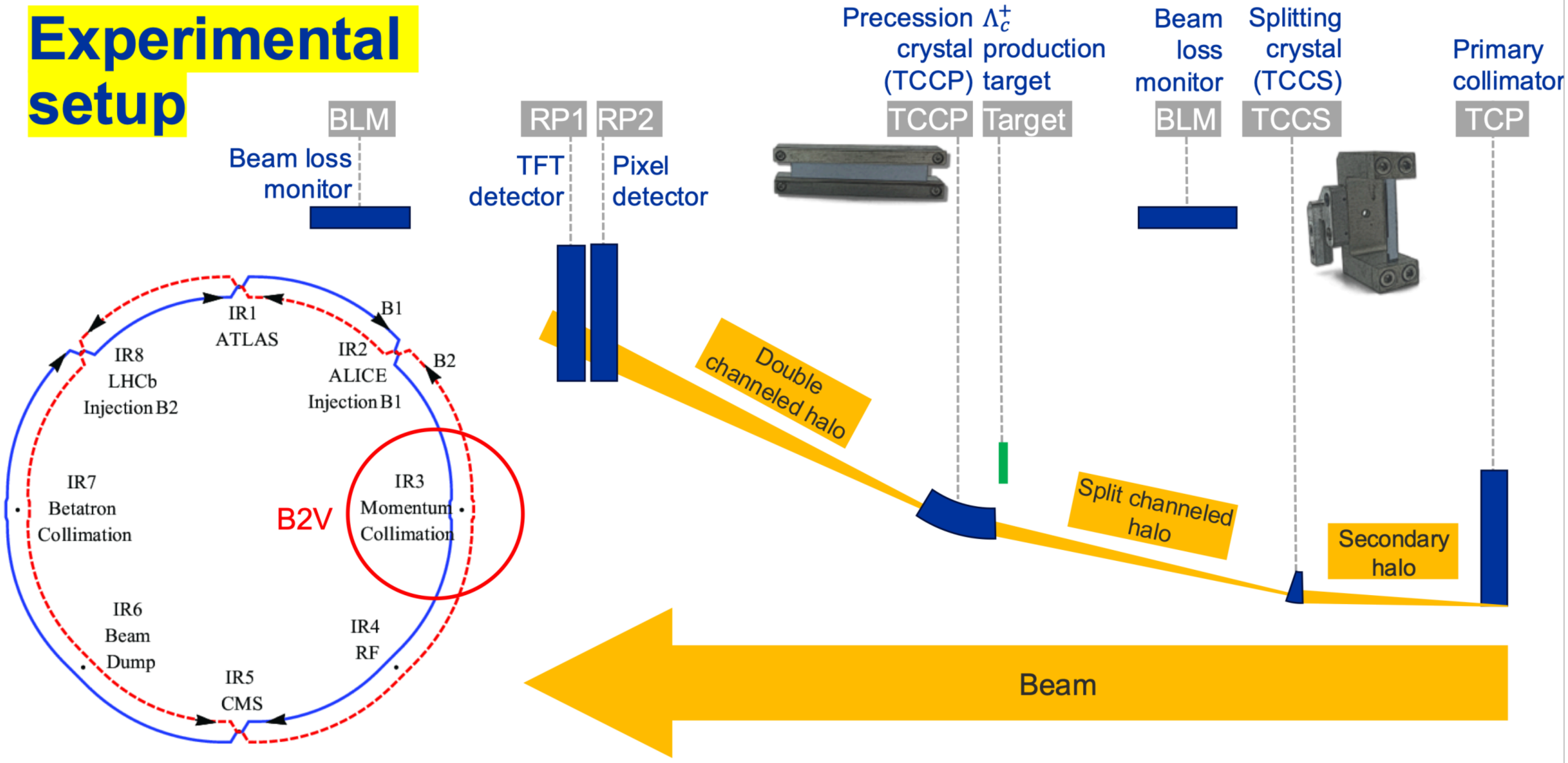
Use 187k $\Xi_c^+ \to pK^-\pi^+$ signal events from semileptonic beauty hadron decays to determine the **amplitude model and Ξ_c^+ polarization**



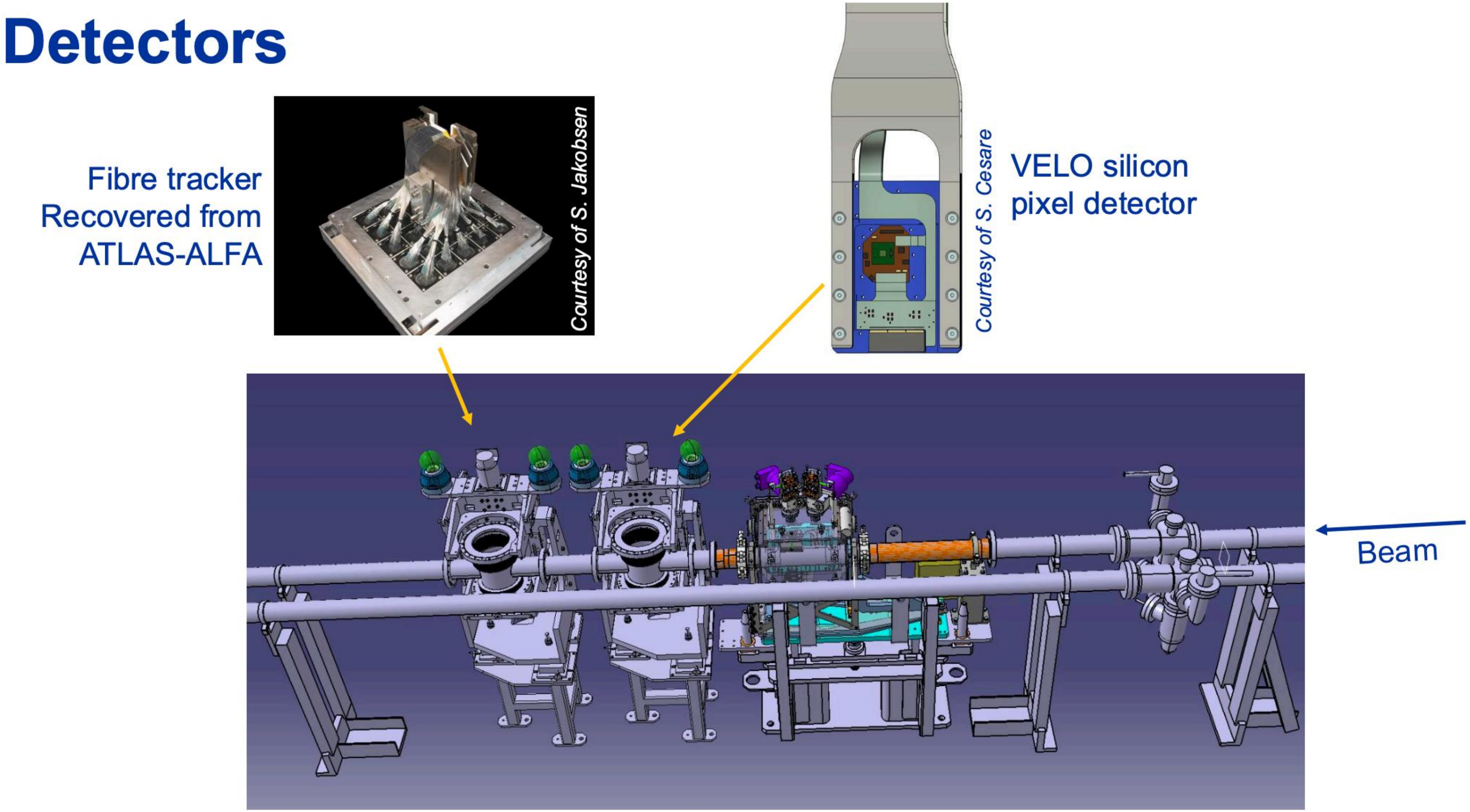


Large sensitivity to polarization (analyzing power). $\boldsymbol{\Xi_c^+ \to pK^-\pi^+}$ **suitable for $\boldsymbol{\Xi_c^+}$ polarization measurements** of produced in fixed-target collisions

TWOCRYST proof-of-principle experiment



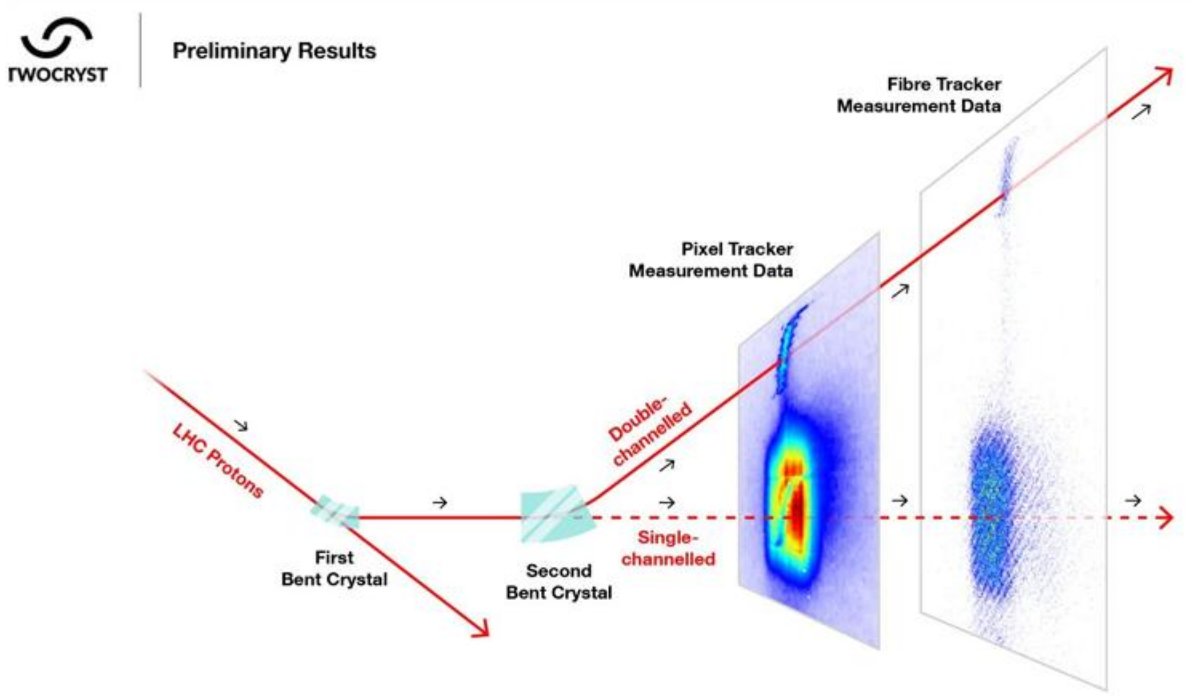
Detector setup



Goniometers, detectors and Roman Pots installed in the 2024/2025 YETS

Preliminary TWOCRYST results at TeV energies

Experimental technique established: successful machine studies conducted during MDs, **double channeling achieved at LHC**

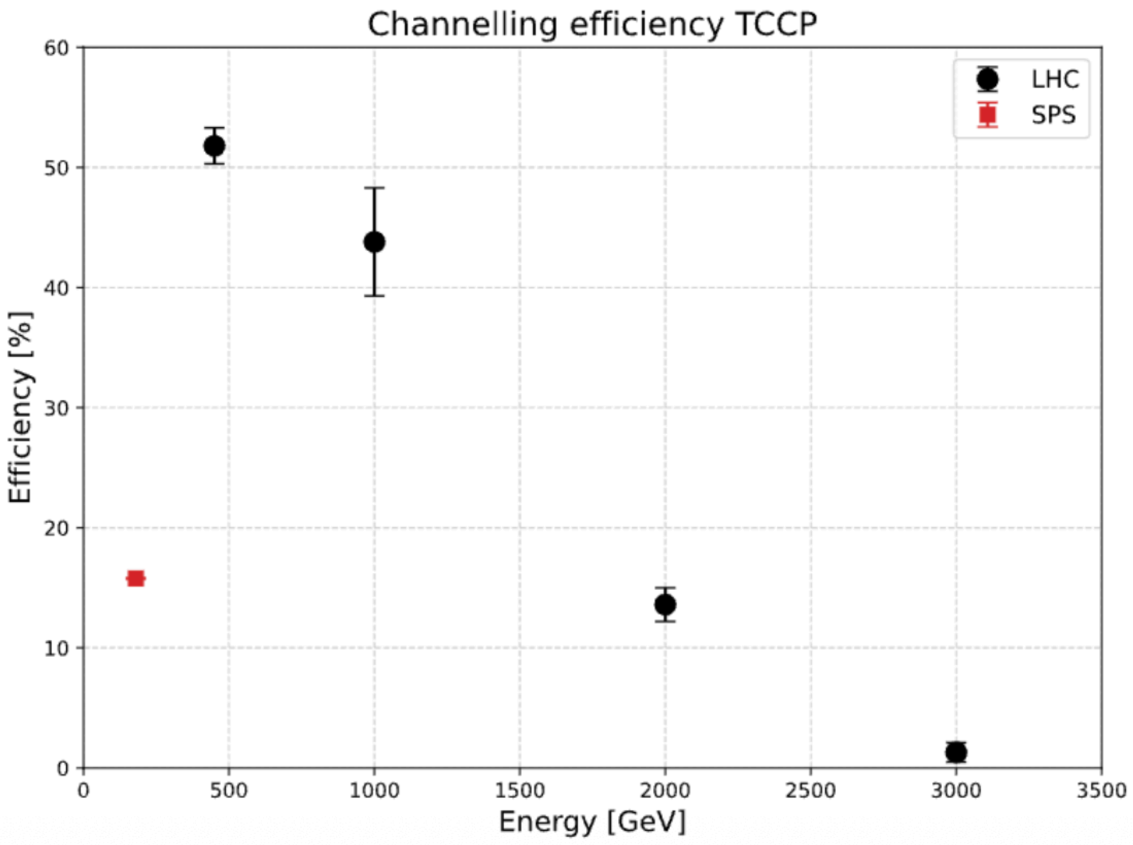


Double channeling using LHC protons from beam halo [CERN news link](#) [INFN news link](#)

CERN Courier article in press

Channeling efficiency at TeV energies

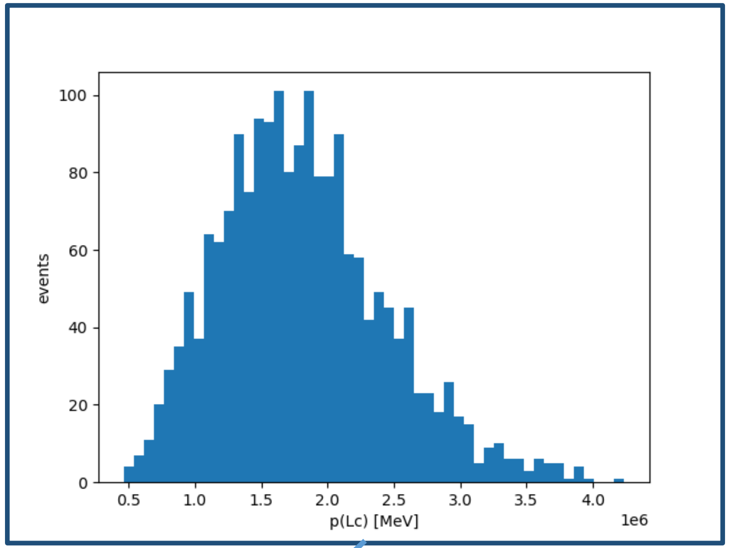
- **First measurement** of channeling efficiency at TeV energies
- Measurement of rate of protons on target at 6.8 TeV in progress

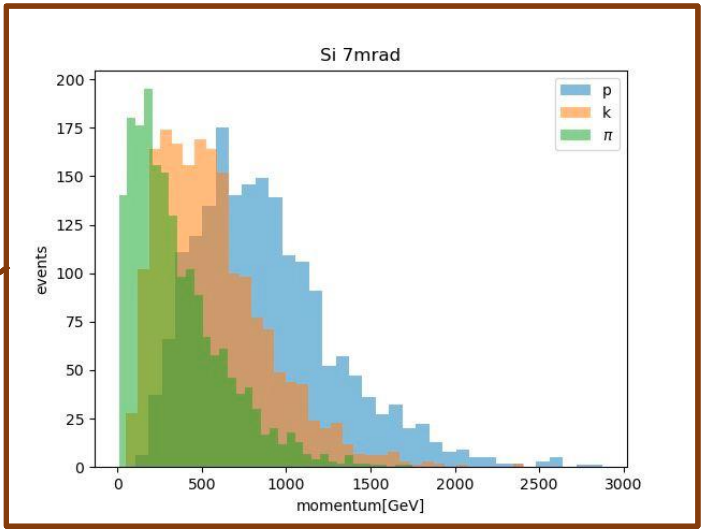


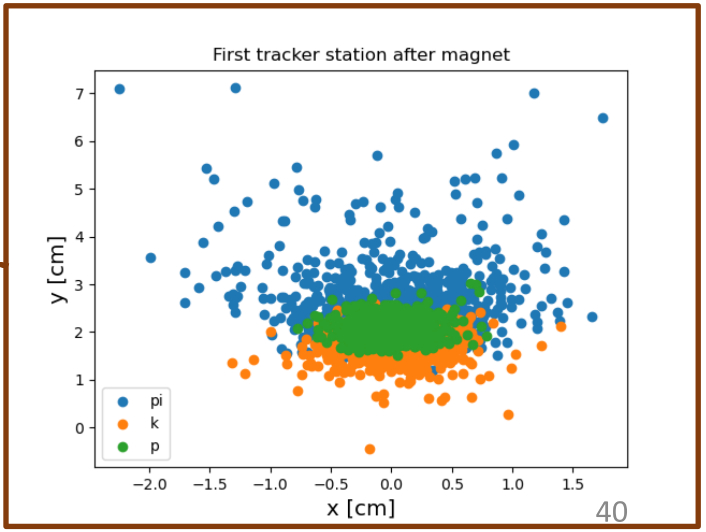
From S. Cesare PhD Thesis
https://doi.org/10.17181/y2499-6bf38

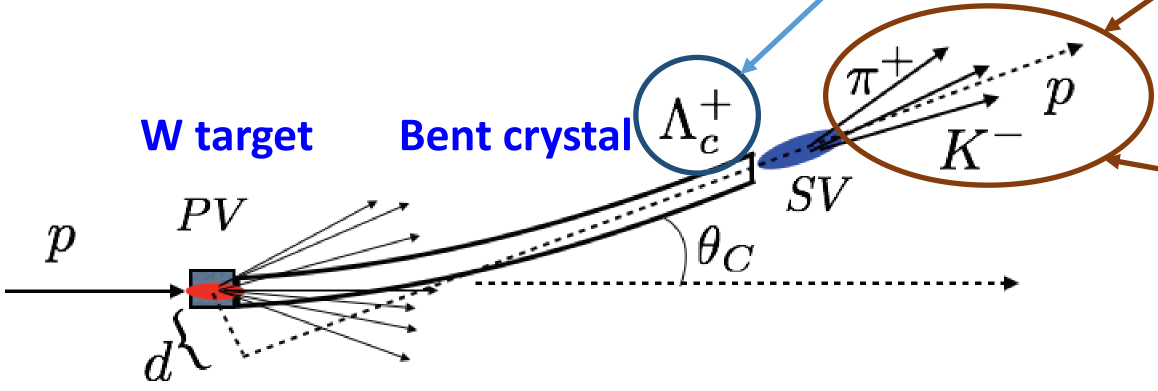
Experiment concept

- With 7 TeV LHC protons and 7 mrad bent crystal
  - ✓ Charm baryons produced in a **very forward** direction
  - ✓ Very high momentum, higher than **1 TeV**



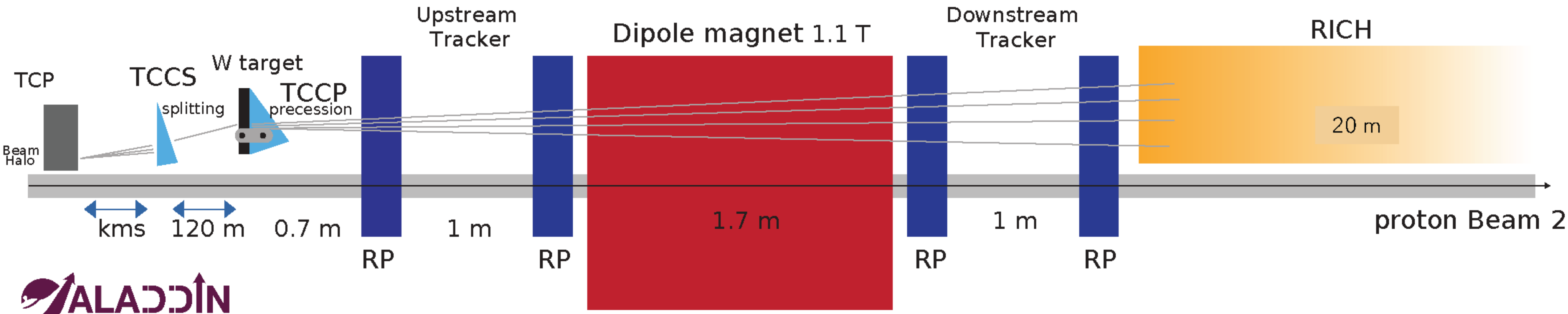


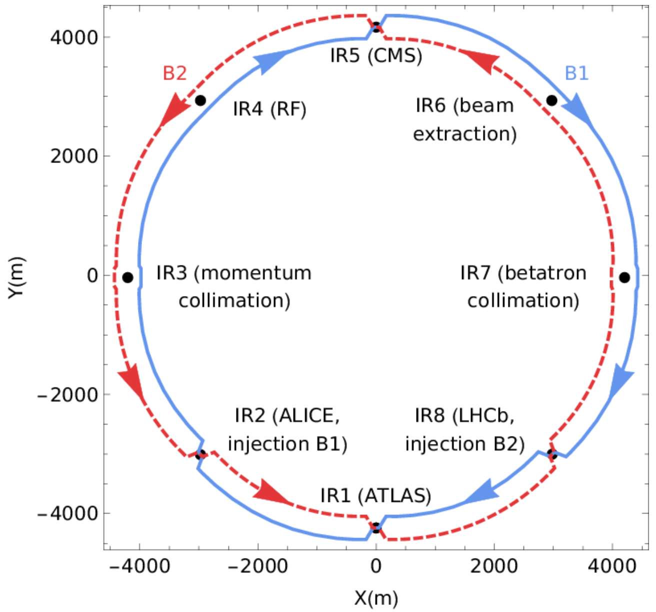




ALADDIN experiment

https://aladdin.web.cern.ch/



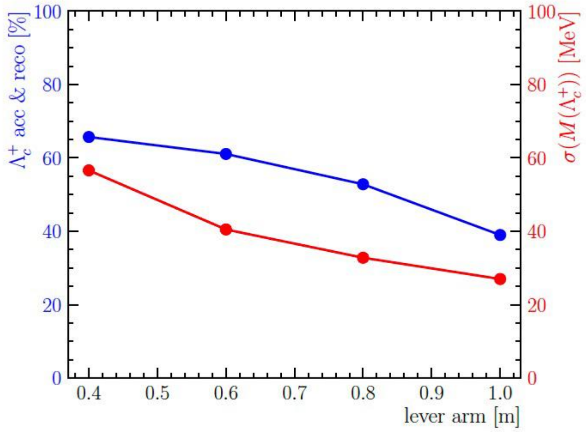


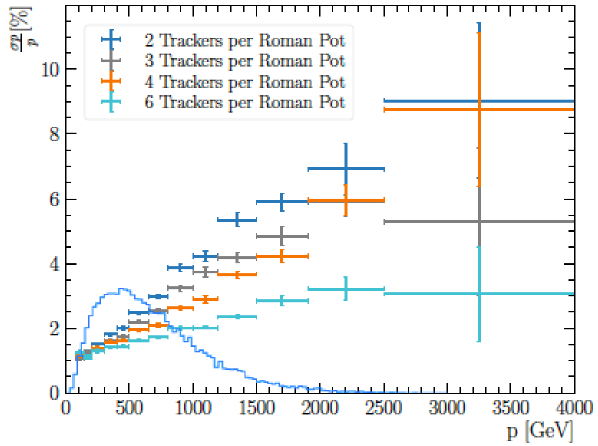
✓ **ALADDIN (An LHC Apparatus for Direct Dipole moment INvestigation)** is an in vacuum fixed-target experiment proposed at LHC for MDM/EDM measurements of charm baryons

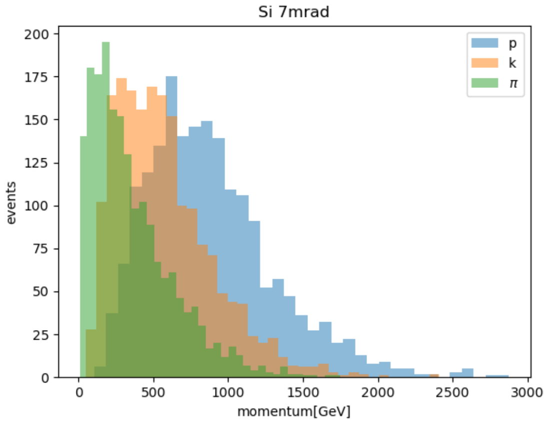
Experimental apparatus:

- **Crystal 1** (TCCS): sec. halo extraction from LHC beam
- **W target** ~ 2 cm
- **Crystal 2** (TCCP): spin precession of charm baryons
- **Spectrometer**: baryon reconstruction with a 1.9 Tm magnet
- Particle identification detector - **RICH**

Detector setup





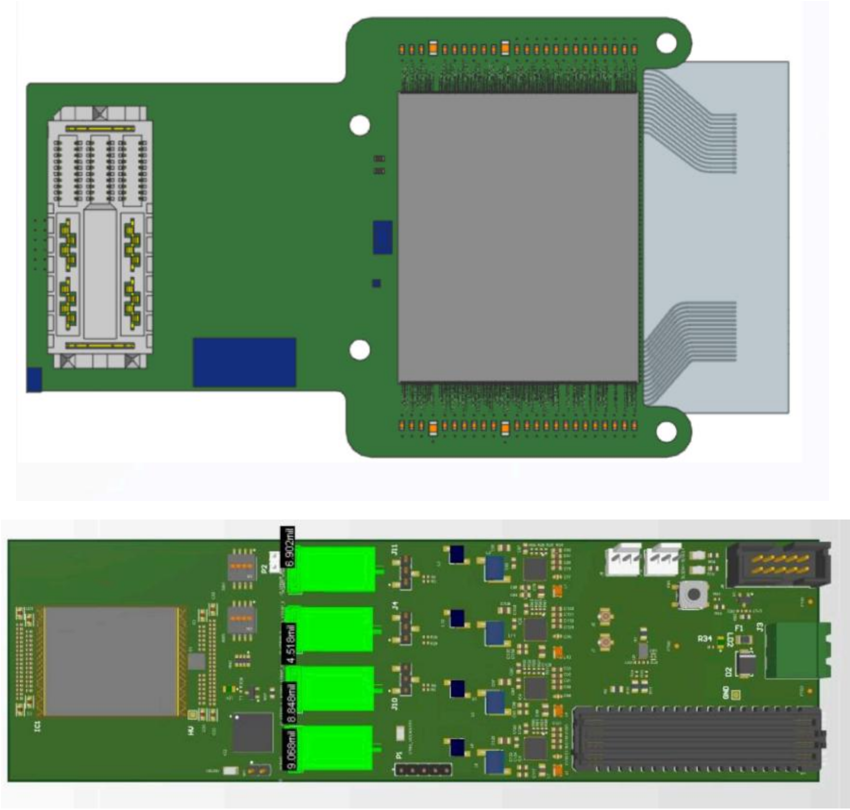


- **Pseudorapidity acceptance** $5 < \eta < 9$
- **Angular resolution** $\approx 15\ \mu\text{rad}$
- **Good momentum & mass resolution** < 25 MeV to separate the signal from misidentified background, eg.
  - ✓ $D^+ \to K^-\pi^+\pi^+$ with one π^+ misidentified to be proton
  - ✓ $D_s^+ \to K^-K^+\pi^+$ with one K^+ misidentified to be proton
  - ✓ have similar cross section, channeling efficiency, and lifetime as Λ_c^+
- Tracker requirements:

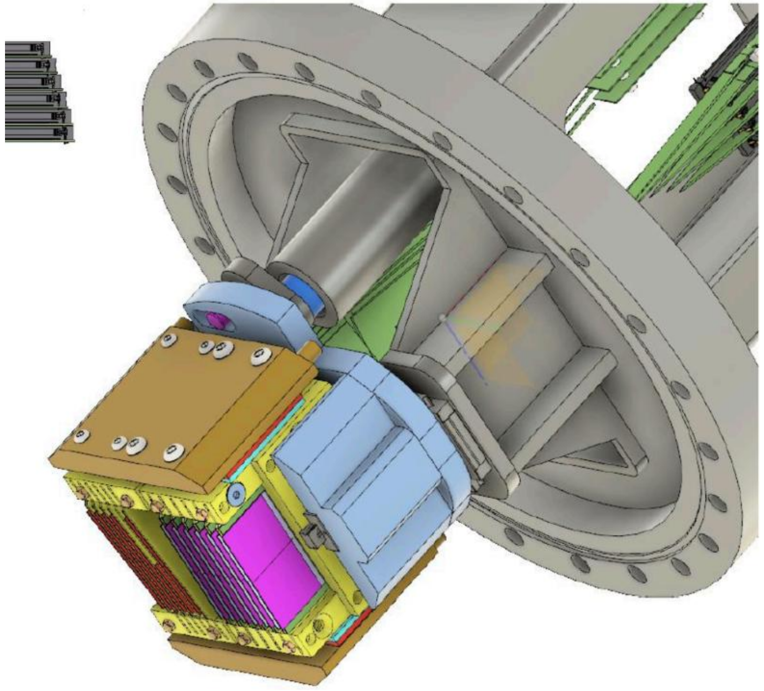
  $\Rightarrow \approx 1\ m$ lever arm (distance between neighboring tracking stations), at least 6 layers/station, 3-4 stations
- Need a RICH for particle ID **up to 1 TeV** to suppress background from misidentification and random combinations

Pixel detector

Exploiting synergies with LHCb upgrade 2 and PPS upgrade

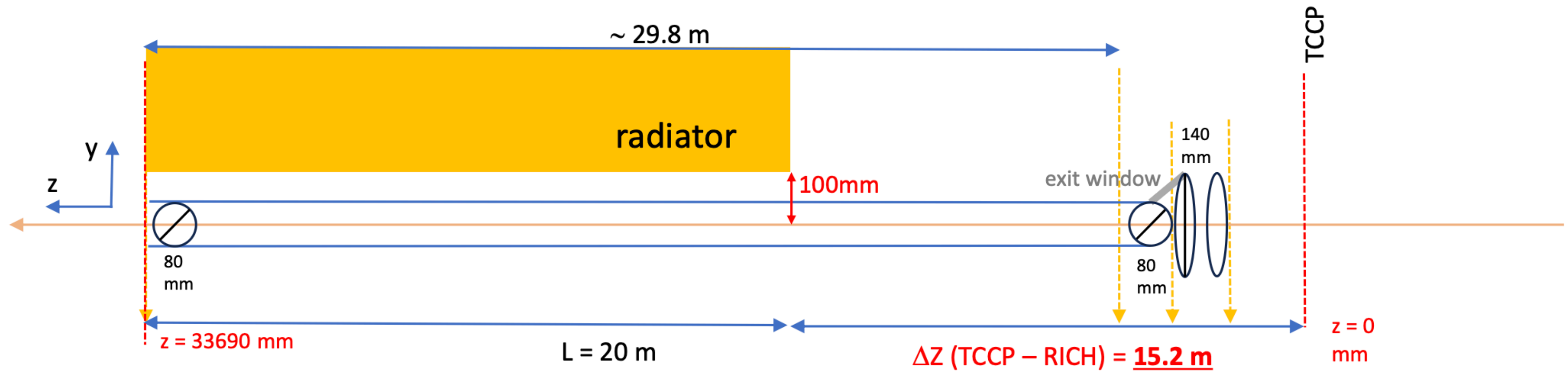


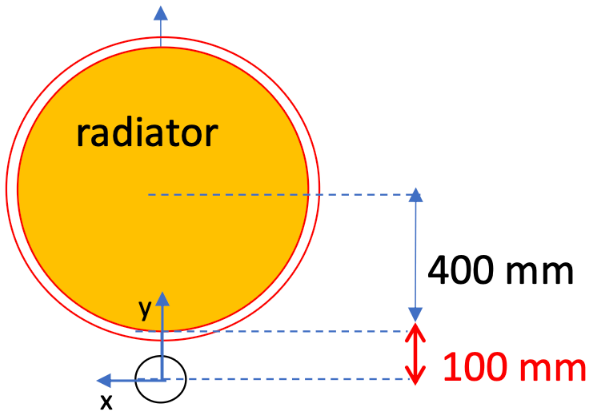
LHCb upgrade 2 pixel readout board prototype



PPS upgrade mechanics/cooling

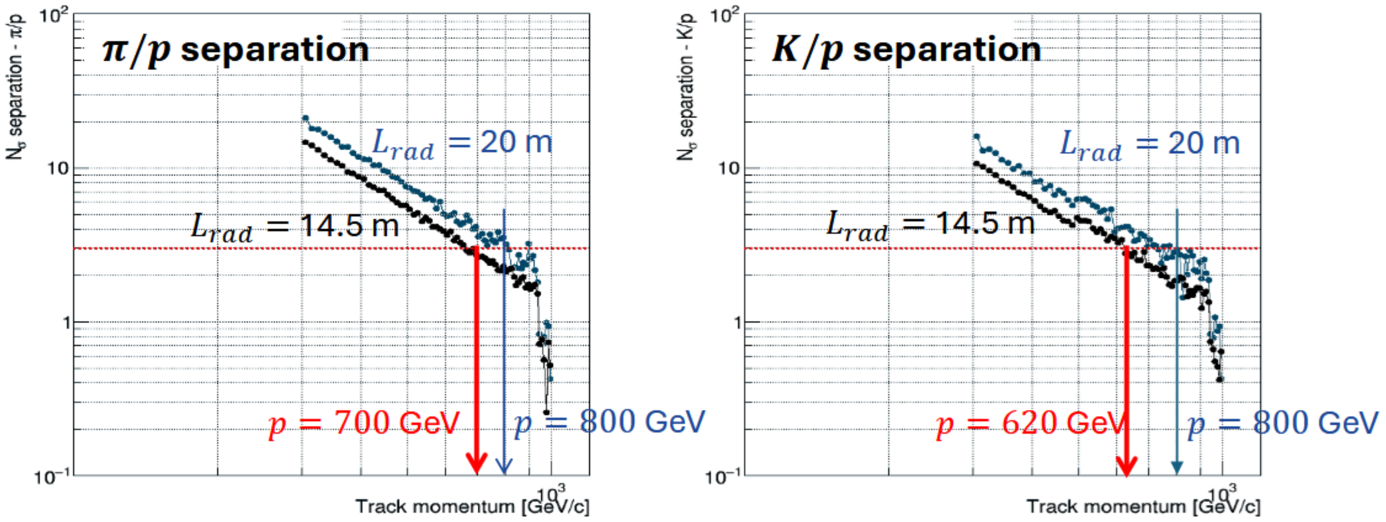
RICH





View in the xy plane at the RICH entrance (not in scale)

Design choice for baseline: 20 m long vessel, 80 cm diameter, filled with Ne (980 mbar, 25 °C, λ=309 nm), single reflection configuration



Sensitivities

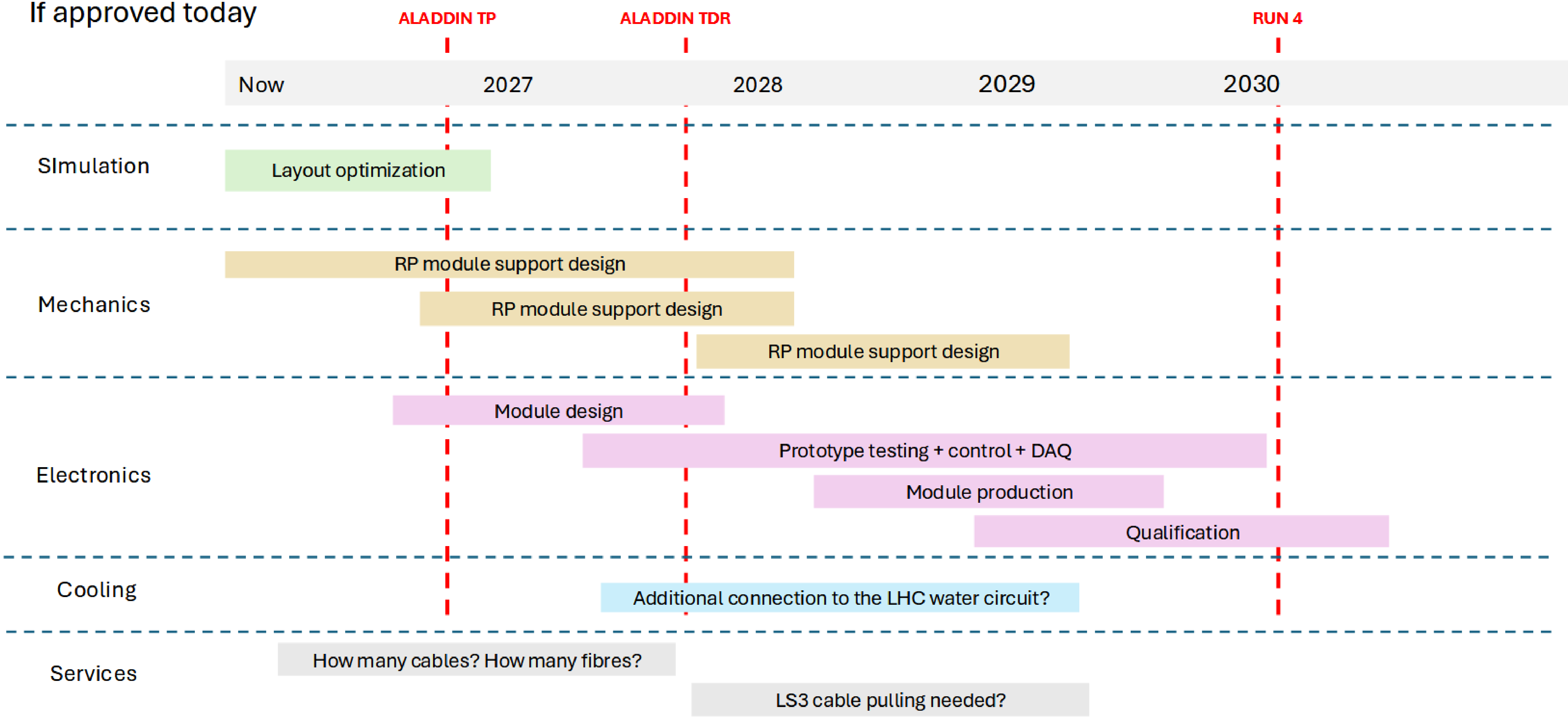
- **First measurements** of **charm baryon** MDM and EDM
  - ✓ 2-year data taking
  - ✓ $10^6\ p/s$
  - ✓ (1.37×10^{13} PoT)
  - ✓ $P \approx 30\%$

Phys. Rev. D103, 072003 (2021)

	Si			Ge	
Deflection angle [mrad]	16	7	5	16	7
Length [cm]	10	7	7	10	7
Λ_c^+ baryon					
a	$\approx -0.03[-0.76]$				
$N_{\rm tot}$ deflected per 10^{10} PoT	3.6	86	162	12	120
$\langle\gamma\rangle$	576	945	1036	717	886
$\langle p_T\rangle$ (GeV/c)	0.67	0.84	0.88	0.73	0.81
$\langle s_x\rangle$	0.09	0.20	0.23	0.13	0.20
$\langle s_y\rangle$	0.22	0.24	0.24	0.23	0.24
$N_{\rm rec}$ $pK^-\pi^+$ only	62	1474	2773	201	2066
$N_{\rm rec}$ all charged	109	2836	5409	367	3940
σ_μ ($\times10^{-2}\ \mu_N$) all charged	4.1	1.2	1.1	2.0	1.1
σ_δ ($\times10^{-16} e$ cm) all charged	6.9 [19]	1.5 [4.6]	1.2 [3.1]	3.1 [11]	1.4 [3.8]
Ξ_c^+ baryon					
a	$\approx 0.05[-0.47]$				
$N_{\rm tot}$ deflected per 10^{10} PoT	19	135	215	40	98
$\langle\gamma\rangle$	437	596	641	520	602
$\langle p_T\rangle$ (GeV/c)	0.65	0.74	0.77	0.69	0.74
$\langle s_x\rangle$	0.08	0.16	0.17	0.10	0.14
$\langle s_y\rangle$	0.23	0.27	0.28	0.25	0.26
$N_{\rm rec}$ $\Xi^-\pi^+\pi^+$ only	89	735	1202	205	1096
$N_{\rm rec}$ all charged	227	1939	3198	531	2898
σ_μ ($\times10^{-2}\ \mu_N$) all charged	3.5	1.8	1.8	2.0	1.5
σ_δ ($\times10^{-16} e$ cm) all charged	7.2 [7.7]	3.1 [3.0]	3.0 [2.5]	3.6 [5.5]	2.9 [2.3]

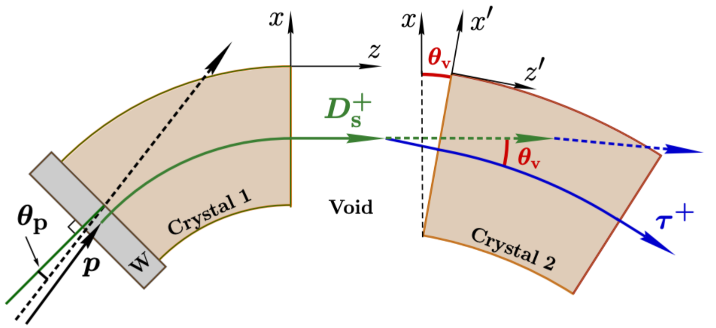
Timeline

If approved today

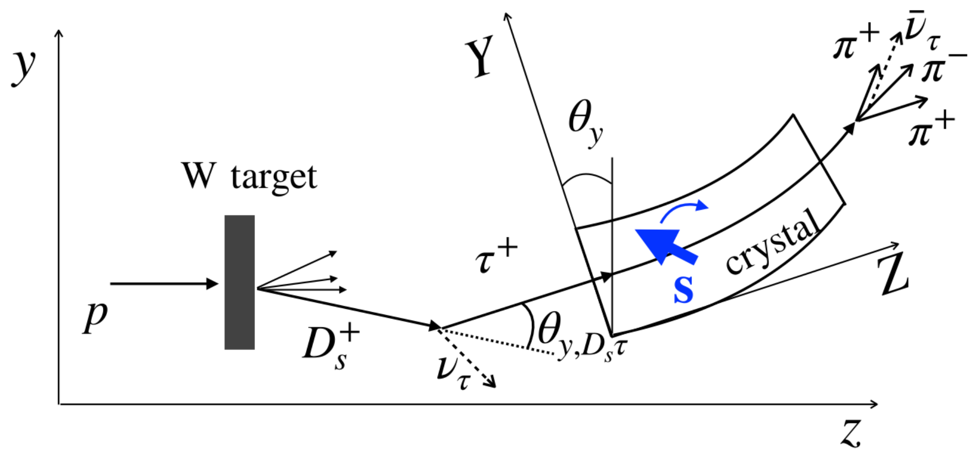


Possibility for τ MEDM

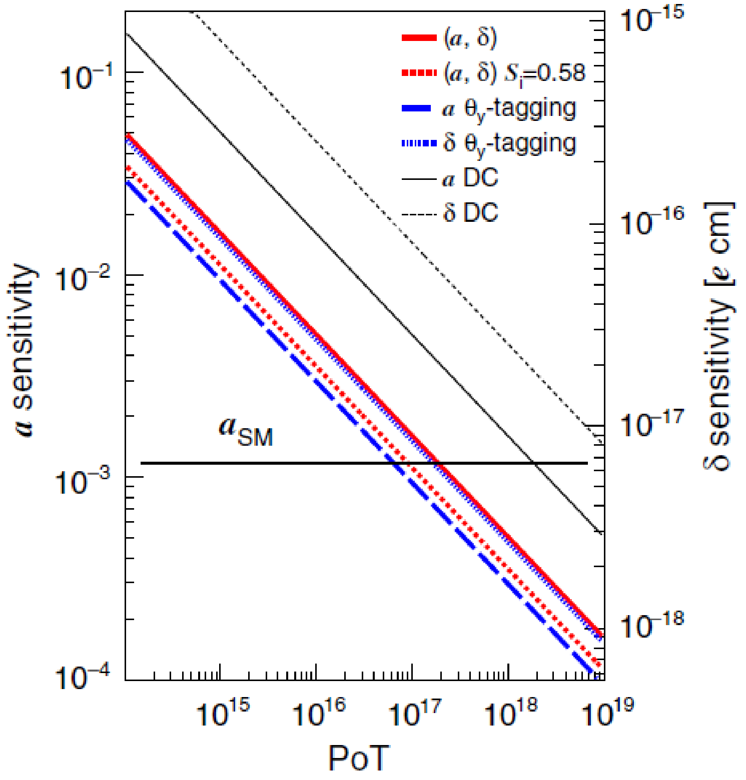
- Opportunity for **other measurements** in the **very forward region**, $5 < \eta < 9$, i.e.
- **τ MEDM**, cross section of charm hadron production, QCD polarisation, J/ψ photoproduction
- Requires much larger #PoT and further R&D: focusing crystals? HI SC magnets?



JHEP 03 (2019) 156



Phys. Rev. Lett. 123 (2019) 011801



4

Summary

Summary

- **Electric and magnetic dipole moments** are of great significance in the search for new source of matter-antimatter imbalance and study the internal structure of fundamental particles
- New measurement of $\boldsymbol{\Lambda}$ **dipole moments** at LHCb is ongoing
- A new experiment, ALADDIN, is proposed and designed at LHC to measure the **electric and magnetic dipole moments of charmed baryons** for the first time
- The electric and magnetic dipole moments of $\boldsymbol{\tau}$ **lepton** are possible to be measured in the future

谢谢

Thank you

ขอบคุณ

T track reconstruction

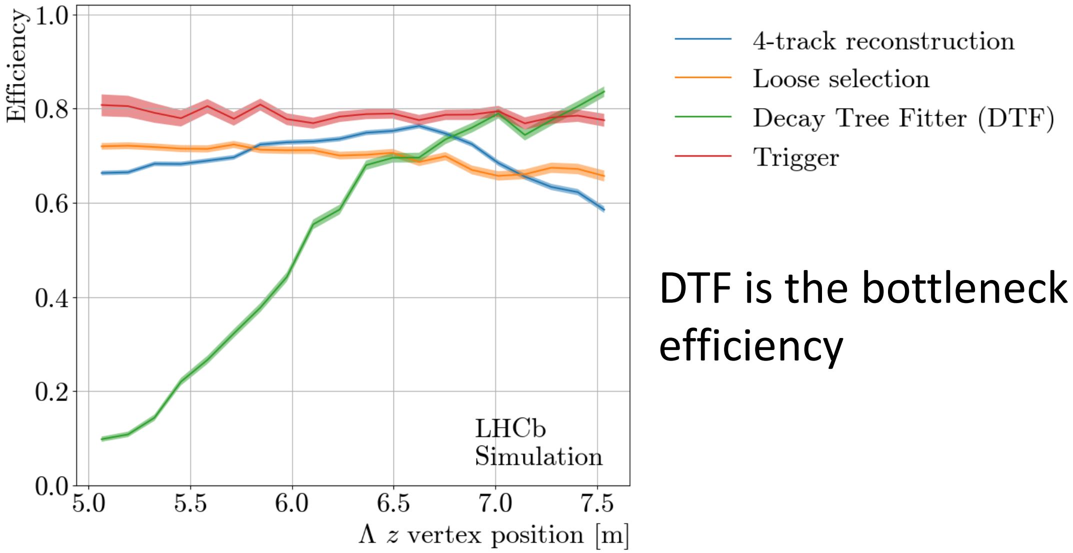
[Long-lived particle reconstruction downstream of the LHCb magnet. Eur. Phys. J. C 85, 7 (2025).]

Reconstruction challenges linked to:

- low magnetic field strength
- few tracking stations

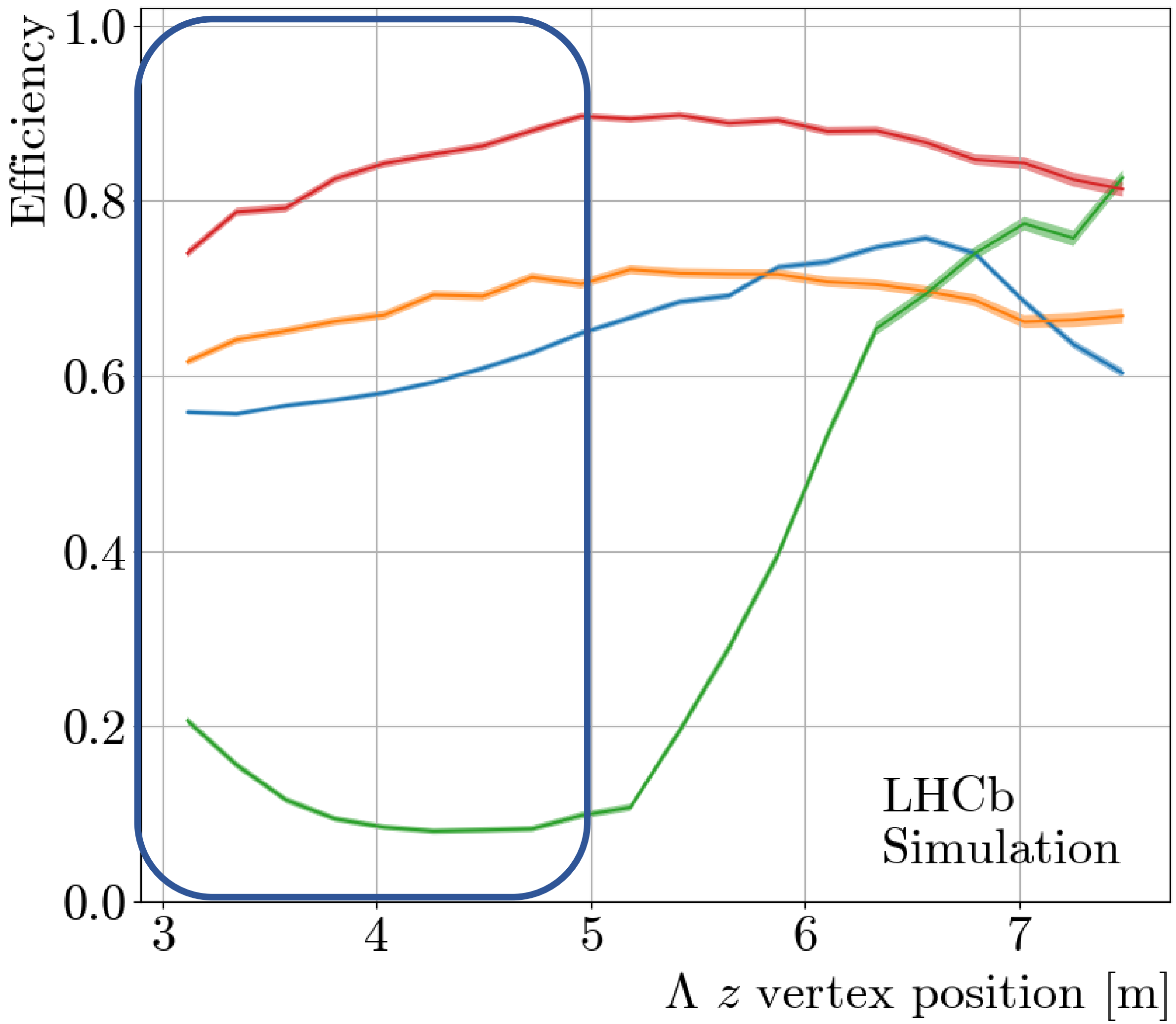
◦ poor **momentum resolution of ~20%** (0.5-1% for Long tracks) : **improved** to **4.5%**

◦ long **propagation** distances from T stations to magnet region → need **RungeKutta** instead of linear extrapolator



DTF is the bottleneck of the efficiency

T track reconstruction



[For more details see Fernando's talk at RTA DPA meeting]

Improvements introduced by FTF (offline tool):

- Residuals evaluation at 1st track measurement
- Global **Runge Kutta (RK)** model instead of usual linear approximation at estimated vertex
- Dedicated and fast RK model
- Optimized **seeding**

This allows us to:
- Increase the efficiency
- **Enlarged** reconstruction region for TT vertex: **(5,8) m** → **(3,8) m**

Resulting in improved momentum, mass and vertex resolutions

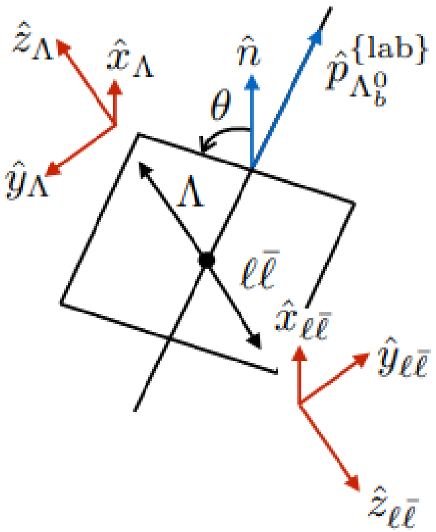
Strategy

Definitions as in Λ_b^0 polarization analysis with LL (arXiv:2004.10563v2)

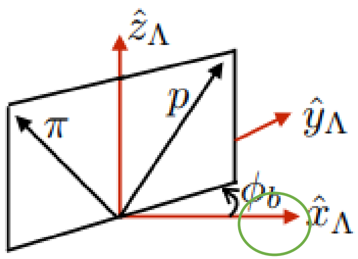
$$\hat{z}_\Lambda = \hat{p}_\Lambda^{\{\Lambda_b^0\}}$$
$$\hat{y}_\Lambda = \hat{n} \times \hat{p}_\Lambda^{\Lambda_b^0}$$

$$\hat{z}_{\ell\bar{\ell}} = \hat{p}_{\ell\bar{\ell}}^{\{\Lambda_b^0\}}$$
$$\hat{y}_{\ell\bar{\ell}} = \hat{n} \times \hat{p}_{\ell\bar{\ell}}^{\{\Lambda_b^0\}}$$

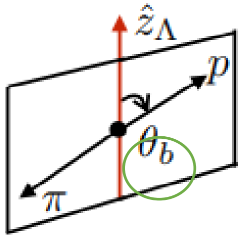
Λ_b^0 rest-frame



Λ_b^0 rest-frame



Λ rest-frame

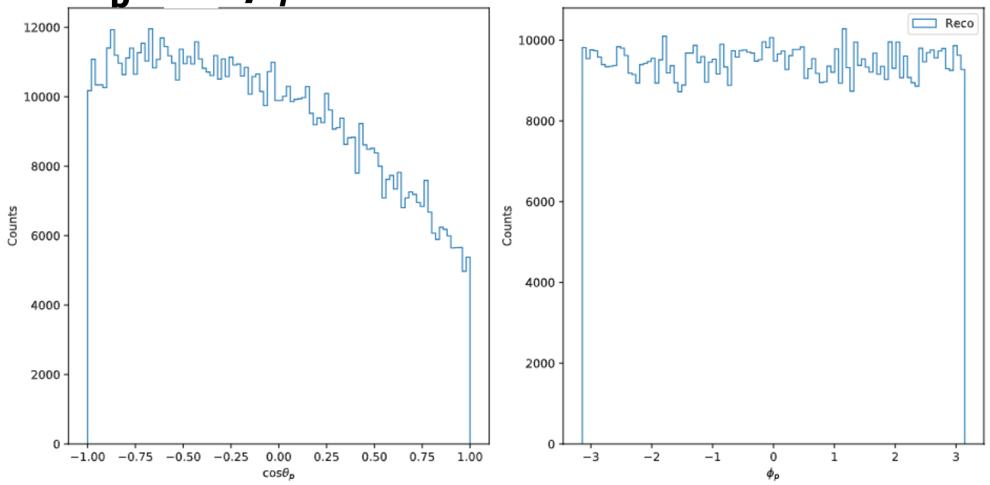


$$\hat{z}_\Lambda^{\{\Lambda\}} = -\hat{p}_{\ell\bar{\ell}}^{\{\Lambda\}}$$

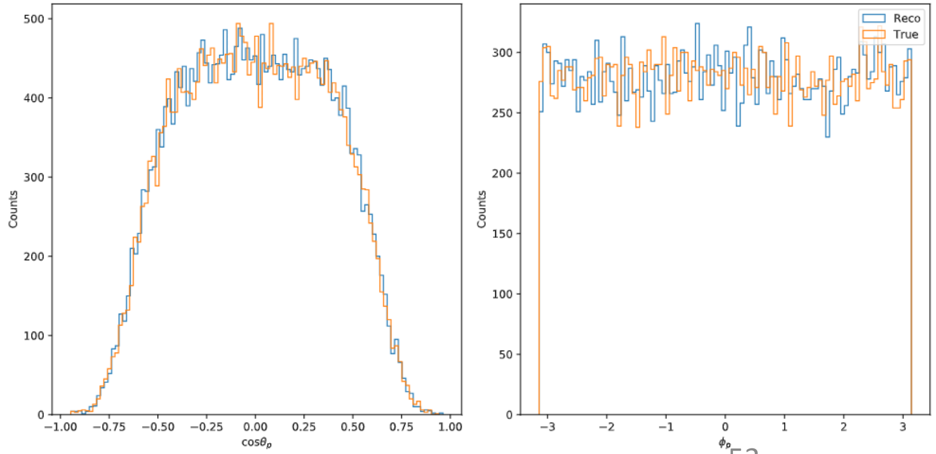
$$\boldsymbol{n} = \frac{\boldsymbol{p}_{\rm inc} \times \boldsymbol{p}_{\Lambda_b^0}}{|\boldsymbol{p}_{\rm inc} \times \boldsymbol{p}_{\Lambda_b^0}|}$$
$$\hat{\boldsymbol{z}}^\Lambda = \hat{\boldsymbol{p}}_\Lambda^{\Lambda_b^0},$$
$$\hat{\boldsymbol{y}}^\Lambda = \hat{\boldsymbol{n}} \times \hat{\boldsymbol{p}}_\Lambda^{\Lambda_b^0},$$
$$\hat{\boldsymbol{x}}^\Lambda = \hat{\boldsymbol{y}}_\Lambda \times \hat{\boldsymbol{z}}_\Lambda.$$

$$\cos\theta_p = \cos\theta_p^\Lambda = \hat{\boldsymbol{z}}^\Lambda \cdot \hat{\boldsymbol{p}}_p^\Lambda = \hat{\boldsymbol{p}}_\Lambda^{\Lambda_b^0} \cdot \hat{\boldsymbol{p}}_p^\Lambda$$
$$\phi_p = \phi_p^\Lambda = \mathrm{atan2}(\hat{\boldsymbol{y}}^\Lambda \cdot \hat{\boldsymbol{p}}_p^\Lambda, \hat{\boldsymbol{y}}^\Lambda \cdot \hat{\boldsymbol{p}}_p^\Lambda)$$

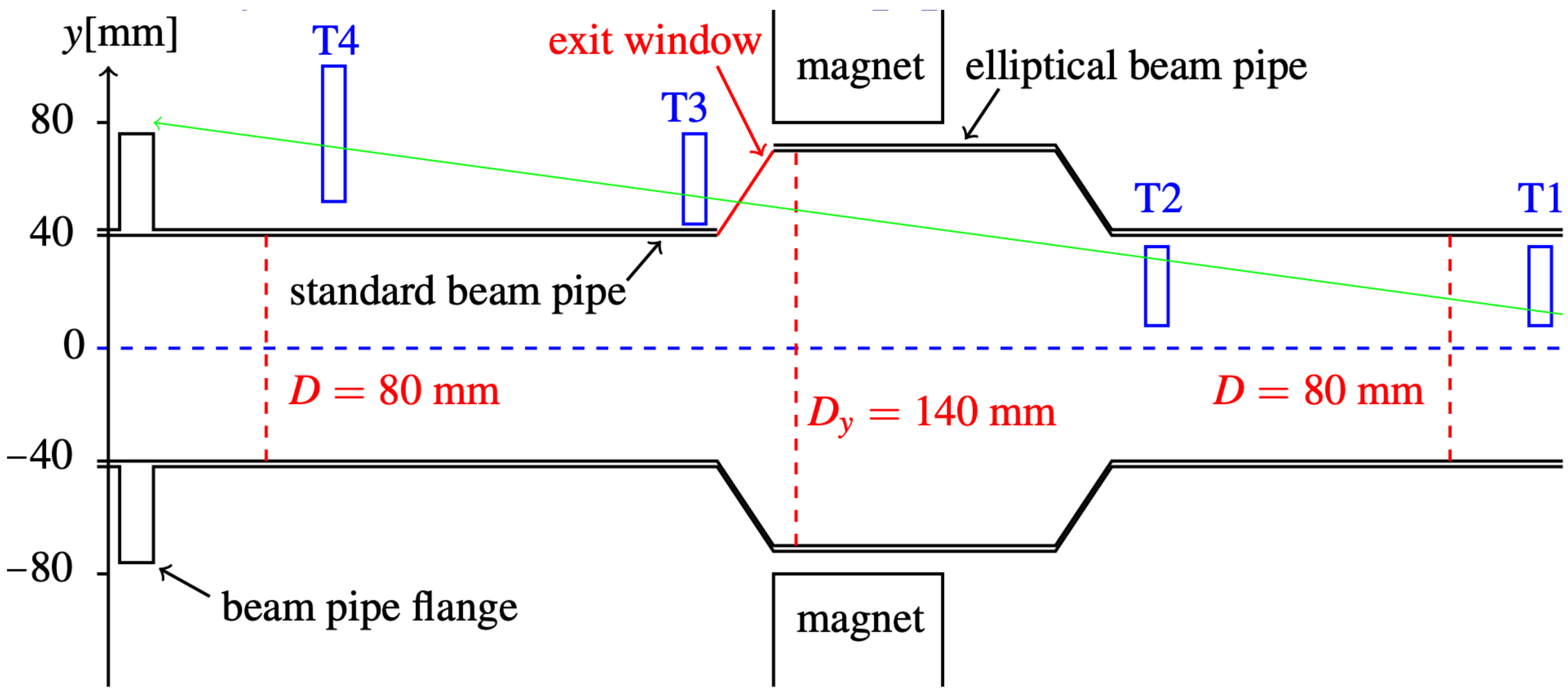
$\Lambda_b^0 \rightarrow J/\psi\, \Lambda$



$B^0 \rightarrow J/\psi\, K_s^0$



ALADDIN experiment



Try to minimize the impact on the beam pipe modifications. Above, the downstream tracking stations are positioned outside the vacuum